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RESEARCH ARTICLE

Qualitative graphing in an authentic inquiry context: How construction and critique help middle school students to reason about cancer

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Abstract

Inquiry instruction often neglects graphing. It gives students few opportunities to develop the knowledge and skills necessary to take advantage of graphs, and which are called for by current science education standards. Yet, it is not well known how to support graphing skills, particularly within middle school science inquiry contexts. Using qualitative graphs is a promising, but underexplored approach. In contrast to quantitative graphs, which can lead students to focus too narrowly on the mechanics of plotting points, qualitative graphs can encourage students to relate graphical representations to their conceptual meaning. Guided by the Knowledge Integration framework, which recognizes and guides students in integrating their diverse ideas about science, we incorporated qualitative graphing activities into a seventh grade web-based inquiry unit about cell division and cancer treatment. In Study 1, we characterized the kinds of graphs students generated in terms of their integration of graphical and scientific knowledge. We also found that students (n = 30) using the unit made significant learning gains based on their pretest to post-test scores. In Study 2, we compared students' performance in two versions of the same unit: One that had students construct, and second that had them critique qualitative graphs. Results showed that both activities had distinct benefits, and improved students' (n = 117) integrated understanding of graphs and science. Specifically, critiquing graphs helped students improve their scientific explanations within the unit, while constructing graphs led students to link key science ideas within both their in-unit and post-unit explanations. We discuss the relative affordances and constraints of critique and construction activities, and observe students' common misunderstandings of graphs. In all, this study offers a critical exploration of how to design instruction that simultaneously supports students' science and graph understanding within complex inquiry contexts.

KEYWORDS

cell biology, curriculum design, graphs, knowledge integration, middle school, student learning, technology

1 | INTRODUCTION

This study responds to the contemporary need for students to use graphs to interpret, 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). It contributes insight into students' abilities to connect graphing and science knowledge through constructing and critiquing graphs, which are critical aspects of expert practice (Ainsworth, Prain, & Tytler, 2011; Arsenault, Smith, & Beauchamp, 2006). We explore a qualitative approach to graphing, by which shapes of trends are sketched onto axes rather than precisely plotted as in the quantitative approach typical in schools (Cobb, 1999; Lai et al., 2016; Watson, 2008). We explore how a qualitative approach to graphing can support students' knowledge integration (KI), that is, their ability to sort out and connect multiple ideas into a coherent explanation of phenomena. In Study 1, we investigated how the incorporation of qualitative graphing into a web-based science inquiry unit supported middle school students in connecting science concepts to graphs. In Study 2, we investigated the value of constructing and critiquing qualitative graphs supporting students' KI.

2 | BACKGROUND AND THEORETICAL FRAMEWORK

2.1 | Finding the synergy between graph and science understanding

All learners require a degree of graph literacy to construct and critique arguments, and to make informed decisions about personal and policy issues (e.g., Round & Campbell, 2013; Wiley et al., 2009). Graphs serve to persuade and inform citizens of important societal and environmental trends, and are inseparable from reasoning and discourse in professional science (e.g., Latour & Woolgar, 1986; Lynch, 1985). Yet, this critical role of graphs in everyday and scientific practice is not often captured in typical K-12 curricula. Despite widespread recognition of the importance of graphs in science, most students first encounter them as linear functions in their mathematics courses (Cobb, 1999; Watson, 2008). Less often do students encounter graphs that feature noninteger values, oscillations, and exponential growth, which are common in professional science, and which can moreover support students' understanding of complex science topics (Mokros & Tinker, 1987). The lack of opportunity for students to use graphs as tools during extended science inquiry activities may be one reason that students struggle to understand and to effectively use graphs in science contexts. It may also explain why some students fail to succeed in science more generally (Gal, 2002; Galesic & Garcia-Retamero, 2013; Gallimore, 1990; Jarman, McClune, Pyle, & Braband, 2012), and that even adults with advanced science degrees can lack the ability to use graphs in contexts that impact their lives (OECD, 2006; Roth, McGinn, & Bowen, 1998).

2.2 | Graph construction and critique as ways to promote knowledge integration

Our work is based on the KI framework, a constructivist view of learning that recognizes and builds on students' diverse, incomplete, and often conflicting ideas about scientific phenomena (diSessa, 1988, 1993; Potvin & Cyr, 2017; Shtulman & Valcarcel, 2012). KI offers an instructional pattern based on extensive longitudinal and classroom research (Linn & Eylon, 2011) that supports students in developing coherent science understanding through cycles of eliciting students' existing ideas; helping them to explore new normative ideas; and continually guiding them in distinguishing, organizing, and reflecting upon those ideas.

Graphs have important roles in science KI. They enable critical inquiry practices, such as exploring, making inferences, explaining, and communicating about interactions and processes within complex systems (Ainsworth, 2006; Shah & Hoeffner, 2002). By visualizing data, graphs highlight patterns and events that are not otherwise apparent (Friel, Curcio, & Bright, 2001; Wu & Krajcik, 2006). Recognizing this information can help with devising and evaluating explanations of complex science problems.

Effective science activities involve coordinating an understanding of the science domain with an understanding of the representational language of graphs. To be successful in this, students must integrate their understanding of graphs and science: They must encode a graph's visual features and relate these to the science concepts that these represent (e.g., Friel et al., 2001; Shah & Hoeffner, 2002). More specifically, competency in graphing involves the interdependent abilities of comprehending, critiquing, and constructing graphs (Shah & Hoeffner, 2002). Comprehending graphs requires learners to encode visual features (e.g., identify a line's slope or a grouping of points as meaningful); make conceptual relations (e.g., interpret a line's decreasing slope in a plot of human population vs. time as a decrease in numbers of people); and understand these in the context of the relevant discipline. Critiquing graphs requires, among other things, that students comprehend and interpret the conceptual meaning underlying a graph, and evaluate its effectiveness at conveying an argument. Whereas both graph comprehension and critique involve reacting to given information, graph construction is a generative activity that is distinct from, yet just as important as critique (Leinhardt, Zaslavsky, & Stein, 1990). It requires that learners move from raw data or abstract functions, and work within the formal rules of a representational system to visualize relationships (Barclay, 1985; Dori & Sasson, 2008; Hammer, Sherin, & Kolpakowski, 1991; Latour, 1990; Leinhardt et al., 1990). By constructing graphs, students can visually demonstrate how they make sense of scientific information. Thus, graph construction can be a useful assessment of students' science learning.

2.3 | Students' difficulties with graphing

Despite the prominence of graph competence in national standards (National Research Council, 2012), graphs receive little attention in classroom instruction and standardized assessments (Miller & Linn, 2013; Yeh & McTigue, 2009). Not surprisingly, research finds that students struggle in all areas of graphing, from comprehension to construction (OECD, 2006). Reading, critiquing, and constructing graphs challenge students who are still developing their understanding of both science and of graphs. For example, they struggle to use graphs as evidence to support arguments (Lovett & Chang, 2007); they read graphs as literal pictures rather than acknowledge the 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 other representational forms that are irrelevant to the contexts at hand (see review by Leinhardt et al., 1990). Consistent with prior research, Lai et al. (2016) found that middle school students struggled to recognize and interpret relationships depicted in visual features, such as trends, shapes, and noise. Students struggled to translate narratives of scientific phenomena into graphs: They provided superficial visual descriptions of graphs rather than descriptions grounded in science. For example, students faltered in their efforts to interpret common graphical patterns, such as curve shapes and noise when making sense of global climate change or growth curves. In constructing graphs, students tended to create 1-point graphs, to generate a series of graphs to represent a single factor, and to graph an increasing linear function regardless of the actual trend (Mevarech & Kramarsky, 1997).

Current approaches to graph instruction may contribute to students' difficulties with graphs. Most documented examples of graphing instruction are in the domain of mathematics. They tend to take discrete, algebraic approaches to concepts such as functions, which can mire students in mundane tasks (e.g., plotting data points), and emphasize students' misunderstandings of graphs rather than their abilities with them. Moving beyond this primarily quantitative perspective on graphing to one that places graphs within a social context can promote coherent understanding (Bowen, Roth, & McGinn, 1999; Pozzer-Ardenghi & Roth, 2010). Rather than viewing graphing as decoding and constructing symbols in simplified step-by-step exercises disconnected from science, a social-practice perspective recognizes graphing as a situated, context-dependent practice. Essentially, it argues that a graph's meaning is constructed through its authentic use, and that expertise is honed through integrating graphing and disciplinary insights. From this perspective, learners benefit by creating narrative explanations that connect graphs to their underlying science.

Several research programs integrate graphing into social-practice oriented inquiry-based activities. These cover domains including climate science (e.g., Rudd, 2014), animal behavior (e.g., Lou, Hooper, & Blanchard, 2016), physics and chemistry (e.g., Greene, Anderson, O'Malley, & Lobczowksi, 2018), microbiology (Hossain, Bumbacher, Blikstein, & Riedel-Kruse, 2017), population ecology (e.g., Malone, Schunn, & Schuchardt, 2018), and computational thinking (e.g., Matsumoto & Cao, 2017). Technology-enhanced environments moreover incorporate tools to support students' data collection and graphing, including probeware (Bernhard, 2014; Gašparík, Prokša, & Drozdíková, 2017); oscilloscopes (Bernhard, 2015); public data sets (Rudd, 2014); automated feedback (e.g., Vitale et al., 2015); Kinect sensors, and large scale full-body visualizations (Anderson & Wall, 2016; Kang, Lindgren, & Planey, 2018). Each of these examples rest in the belief that making graphing integral to realistic science inquiry activities can support students in connecting their everyday experiences with phenomena (e.g., the feeling of motion) to the abstract representations of those phenomena (e.g., graphs of time vs. position) (Lai et al., 2016).

2.4 | The promise of qualitative graphing in social-practice oriented science inquiry contexts

This study explores the value of a qualitative, social practice approach to graphing in science inquiry. Typical algebraic approaches to graphing fail to take advantage of students' situation-based intuitions regarding functions; as such, they are unlikely to prepare students to connect graphs to relevant science ideas, nor to convince science teachers to allocate instructional time to using graphs to teach science concepts. Leinhardt et al. (1990) instead propose drawing on students' everyday experiences with functions—which include concepts of variation, dependence, and causality. They recommend a qualitative approach to graphing, by which students focus on identifying global trends from overall graph shapes rather than on pointwise details. In contrast to quantitative approaches to graphing, which emphasize the mechanics of plotting and reading points on axes, a qualitative approach focuses students on sketching and interpreting trends (e.g., changes in temperature, in solution concentrations). Thus, Moore and Thompson (2015) distinguish between using graphs for static shape thinking (viewing graphs as pictures that can be interpreted by learning facts about their properties), and emergent shape thinking (seeing graph shapes in terms of covarying quantities). For example, quantitatively graphing the motion of a pendulum might have learners note the pendulum's position at different time intervals, and to plot, one at a time, points as position on a *y*-axis against time on an *x*-axis. Such an exercise can be completed without conceptual understanding. In contrast, qualitatively graphing a pendulum's motion might have learners sketch the general shape of the pendulum's position over time without necessarily attending to precise coordinates. In doing so, learners are prompted to consciously tie their observations of the swinging pendulum to a representation: They begin to better understand what position and motion mean as a trace in coordinate space. Furthermore, learners' conceptual understanding of the resulting sinusoidal shape is one that they can learn to relate to other phenomena (e.g., predator–prey relationships). Recognizing and representing such trends qualitatively thus frees both students and teachers to attend to the science ideas underlying graph representations.

Research on the shortcomings of quantitative approaches to graph instruction suggests that there may be value in qualitative approaches. For example, undergraduate students participating in a laboratory-based study were asked to either select a graph to match a narrative description of results from a psychology study, or to interpret the graph associated with those results (Pérez-Echeverría, Postigo, & Marín, 2018). Students were moderately able to select appropriate graphs, but even students with psychology background could give only weak conceptual interpretations of those graphs. These authors found students' errors to be based on their focus on straightforward symbol decoding, rather than on interpreting the links between graph shape and conceptual meaning. They attribute their findings to the emphasis in statistics education on syntactic aspects of graphs, and suggest that students might rather benefit from graphing integrated into broader practices such as comparing theories, solving problems, and arguing over competing perspectives (e.g., García-Milá et al., 2016).

Other research found that high school students were unable to identify discrepancies between graphs and incorrect narrative explanations of those graphs (Whitacre & Saul, 2016). Rather than question the given explanations, these students adapted their interpretations of the graphs in an attempt to resolve discrepancies between what was shown, and what was provided as a description. These authors posit that whereas students' school training prepared them to read graph features such as scales, axes, and labels, it did not prepare them to approach graphs critically in terms of their underlying conceptual meaning.

In yet another study, secondary science students learning about energy consumption by constructing graphs in a virtual world experienced difficulty shifting from a procedural orientation to a conceptual one (Krange & Arnseth, 2012). That is, they were challenged to integrate conceptual science reasoning into the technical task of using the virtual world and the spreadsheet. This finding suggests that simply placing graphing within an authentic learning environment may not be enough to support students in linking their knowledge of science and graphing.

Thus incorporating a qualitative approach to graph instruction may permit students to go beyond the data, and to make inferences based on their conceptual understanding of that data. However, interpreting qualitative features of graphs, which requires integrating conceptual and representational understanding, has been shown to be more difficult for middle school students than interpreting quantitative features of graphs, which involves a more straightforward procedural mapping of factual and symbolic information (Hattikudur et al., 2012).

2.5 | The value of instruction that integrates graph and science knowledge

Graph-centered instruction develops students' abilities to use graphs within complex science inquiry activities. For instance, when students construct graphs to capture a scientific phenomenon, they make their thinking apparent and available for assessment. In one study, the graphs that middle school students drew of mass versus volume during their virtual experiments with buoyancy revealed their misunderstandings of density (Vitale, Applebaum & Linn, 2019). In another study, carefully designed guidance supported students in making conceptual connections to graphs. As a case in point, Vitale, Lai & Linn (2014) had eighth grade students read narrative descriptions of objects in motion (e.g., runners training for a race), and to then construct position versus time graphs to represent their understanding. They found that offering animated visual guidance (a graph being animated alongside the motion of objects with a visual scene) helped students to associate their observations of objects in motion to graphic representations of that motion. More specifically, guidance that showed an object's motion based both on students' predicted graphs and on the actual motion described in the narrative (as opposed to only the latter), helped students to distinguish conflicting ideas, and prompted them to revise their initial thinking.

Research shows that qualitative graph construction in mathematics can also improve graph understanding. In a middle school mathematics unit on linear functions, for instance, Kramarski (2004) found that explicit metacognitive instruction during cooperative graph construction activities was effective. In this study, students explained their reasoning and challenged their peers' views, collaborative interactions that helped to reduce students' alternative conceptions of graphs during construction and interpretation activities.

Altogether, the research reviewed above highlights the importance of graph understanding within general science literacy, as well as students' struggles to use graphs. It demonstrates how graphs integrated into complex inquiry instruction can serve to both support and reveal students' conceptual science understanding. It also suggests that effective support for students to grow in their graph competence involves carefully designed guidance to reflect upon and explain their ideas in contexts that engage practices such as prediction, explanation, and argumentation. Whereas these findings suggest the value of incorporating qualitative graphing into science instruction, they also raise questions about *how* to best approach qualitative graphing to support students' science learning. That is, what practices around qualitative graphs might most effectively support students' science and graph KI?

2.6 | Science inquiry learning through graph construction and critique

The abilities to construct and critique graphs are each essential components of metarepresentational competence, which is in turn key to scientific literacy and practice (diSessa & Sherin, 2000). Whereas both construction and critique can engage learners in interpretation, that is, in thinking about how concepts and their representations should be linked (i.e., how ideas should be *integrated*), each of construction and critique can also engage learners to different extents in more specific KI processes. For instance, critiquing graphs can focus learners on adding new ideas and distinguishing among them. That is, viewing given options of graphs can expose learners to new kinds of graphs that they might not otherwise have produced on their own (i.e., *adding* ideas). As well, because different graphs tell different stories, comparing among graphs engages learners in determining their differences and similarities (i.e., *distinguishing* ideas). Meanwhile, constructing graphs can encourage students to consider what they know about how to represent their conceptual understanding (i.e., *elicit* ideas), and to make decisions about which might be the best approach (i.e., *distinguish* ideas). While each of eliciting, adding, and distinguishing ideas contributes to developing an integrated understanding, it is an open question as to which is best to emphasize within a qualitative graphing activity embedded in a realistic inquiry context to promote KI.

To explore this question, we studied the classroom implementation of a web-based middle school unit, in which students learn about mitosis and cell division by qualitatively graphing relationships between cancer and cancer treatment.

2.7 | Incorporating qualitative graphing into an investigation of mitosis and cancer

The middle school science unit, *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), a free, open source learning environment with tools for authoring media-rich content, and for monitoring and guiding students' work. *Mitosis* has, for several years, been regularly used by teachers around the world.

Mitosis introduces students to the process of cell division and the effects of cancer on the body. Central to the unit is a comparative investigation of potential cancer medicines. In pairs on shared computers, students observe animations of cells dividing normally, and of cells treated with each of three different medicine options. Tools incorporated into the environment help students to develop, share, and refine their understanding of cell division and cancer. They propose an evidence-based recommendation for the medicine that they believe would be most effective at stopping cells from dividing, and thus, at treating cancer.

As with other WISE units, *Mitosis* was designed to follow the KI perspective (Linn & Eylon, 2011). We incorporated graphing into *Mitosis* such that engaging in graphing activities would both advance the inquiry narrative and support students in integrating their understanding of key science ideas (Table 1). One key idea is that biological processes are continuous. For example, while scientists have defined and named discrete phases of cell division (interphase, prophase, metaphase, anaphase, and telophase), these are simply names to facilitate discussion among scientists. In *Mitosis*, one activity asks students to pinpoint the frame in an animation of a dividing cell that marked the beginning of a particular phase of division. This exercise is intended to generate debate among student partners, and enable them to realize that the boundaries between phases are subjective, and determined by community consensus.

Continuity is also characteristic of changes in the body's cell numbers, which have important health effects: Normal rates of cell division and cell death achieve a balance that sustains life, whereas unhindered cancerous cell division causes exponential growth that can lead to illness and death. When students understand this, they can see why cancer treatment must stop cell division, but often has side effects.

To support these key ideas, we incorporated graphing activities that capture the continuity of mitosis. The activities asked students to select among possible graph representations, use digital drawing tools to sketch curves on axes, annotate graphs with their interpretations, and share and discuss others' graphs. Notably, the graph shapes featured in these activities were curved. Curves are less familiar shapes to these students than discrete graphs, but they better capture continuous processes such as exponential growth, which is characteristic of cell division. Meanwhile, graph construction activities asked students to sketch general trends rather than to plot points on grids. Such qualitative graphing activities support the kind of conceptual reasoning necessary for students to distinguish the relative effectiveness of different cancer treatments. Students can express and consider predicted outcomes without distraction from the otherwise technical aspects of pointwise plotting tasks.

To explore how middle school students would use qualitative graphs to reason about cancer treatment, we conducted two cycles of design, implementation and iteration on *Mitosis*. In Study 1, we describe how we integrated qualitative graphing activities into the unit's narrative, and explore the effectiveness of the unit in promoting students' integrated conceptual understanding of cancer and mitosis. In Study 2, we describe our subsequent revisions to the graphing activities, and our investigation of the comparative value of constructing vs. critiquing qualitative graphs on students' integrated understanding of mitosis.

3 | STUDY 1

This study describes our initial approach to incorporating graphs into the *Mitosis* unit, and to understanding their effectiveness at supporting students to integrate their understanding of graphs and science. We also capture students' changing notions of the nature of cancer and cancer treatment through the kinds of graphs they generated before and after the unit's enactment. Specifically, this study asks: (i) Do students' gain integrated understanding of cell division, cancer, and cancer treatment following their use of the unit, which incorporates qualitative graphing activities? and (ii) What do the graphs that students generate before and after the unit indicate about their changing conceptual understanding of the underlying science?

3.1 | Introducing graphs into *Mitosis*

We incorporated graphing activities at two points in *Mitosis*. One point was near the beginning of the unit. Here, students learned that in contrast to the division of normal healthy cells, which is controlled

TABLE 1 Summary of activities in the *Mitosis* unit used in Study 2, which mainly differ from Study 1 in the addition of activities 5 and 6

KI process	Activity
Elicit/add	1. What is cancer? Students are introduced to cell division, cancer, and the unit's driving question. They are encouraged to consider why some cells divide faster than others, and to think what might happen if cancerous cells are allowed to continue dividing out of control.
Distinguish/organize/reflect	1 (continued). Normal versus cancerous cell division[a]: Students are shown a graph of cell numbers over time during normal cell division, and are asked to overlay a second curve to show how cancerous cell numbers change, in comparison, over the same period of time.
Elicit/add	2. The phases of cell division: Students distinguish phases of cell division from various pieces of visual evidence: They annotate a microscopic image of cells; they sequence images of cells in various states of division; they indicate the start and stop times of meaningful events in animations and time-lapse videos of dividing cells; and they propose and debate these phases with their classmates using evidence from their observations.
	3. Trade offs and side effects: Students are introduced to the concept of trade-offs. They read a scenario that demonstrates a trade-off, and then describe the trade-offs represented in a selection of images. Students are told that cancer medicines may work by stopping cell division, but that this solution comes with a trade-off to the patient's overall quality of life.
Distinguish	4. Investigating three potential cures: Students compare animations of the division of a normal cell and of a cancerous cell that has been treated by one of three plant-derived medicines.
Organize	4 (continued). Final recommendation: Students sort the observations of each medicine they collected in terms of advantages and disadvantages for treating cancer. They write and revise recommendations for the best cancer medicine after sharing ideas with peers in their class.
Elicit/add/distinguish	5. Cancer treatment options[a]: Students learn about the benefits and tradeoffs of surgery and chemotherapy by interpreting graphs of these treatments' effects on the number of cells in the body.
Organize/reflect	6. Prescribe a treatment[a]: Students consider the effects of a cancer treatment on the body's cells through one of the following activities, to which they were randomly assigned (also see Figure 10): 6a. Critique a graph: Students interpret and critique a fictional doctor's prescribed treatment by examining a graph of its effects on the number of cells in the body. 6b. Construct a graph: Students describe the cancer treatment they would prescribe, and generate and explain a graph to show its effects on the number of cells in the body.
Add/distinguish/ Reflect	7. Discuss others' perspectives[a]: Students use a discussion forum to share and comment on one another's graphs from 6a or 6b and explanations, and then revise their own work in light of others' opinions.

The leftmost column shows the alignment of activities with the knowledge integration (KI) processes that they are intended to support.
[a] Highlights activities that feature graphing.

by a natural control mechanism in the body, the division of cancerous cells proceeds unchecked. At this point, students were shown a curve of normal cell numbers increasing over time, and were asked to overlay a curve that best represents the increase in cancer cell numbers over time (Figure 1). Later in the unit, students watched animations of dividing cells, each of which was treated with a different medicine, and documented their observations. Here, students were asked to select one of six graph options that they believed to best represent the effects of a successful medicine, and to annotate and explain the graph's meaning (Figure 2).

3.2 | Participants and study design

We implemented the unit with 30 students taught by one teacher in a diverse middle school in the Western United States. The teacher had more than 6 years of experience teaching with WISE, and had previously taught earlier versions of the *Mitosis* unit, which did not include graphing activities. Although participants had studied cell structure earlier in the school year, the *Mitosis* unit was their first introduction to cell division and cancer. It was also their first introduction to nonlinear graphs.

Students worked in partners on the unit for approximately 10 consecutive class periods, during which they also individually completed a pretest and post-test. The teacher circulated the classroom and only interjected to offer individual or whole class guidance as required.

3.3 | Pretest and post-test assessments

We created six pretest and post-test items to measure students' learning gains on key concepts and skills targeted by the unit. These items allowed students to demonstrate their KI by constructing

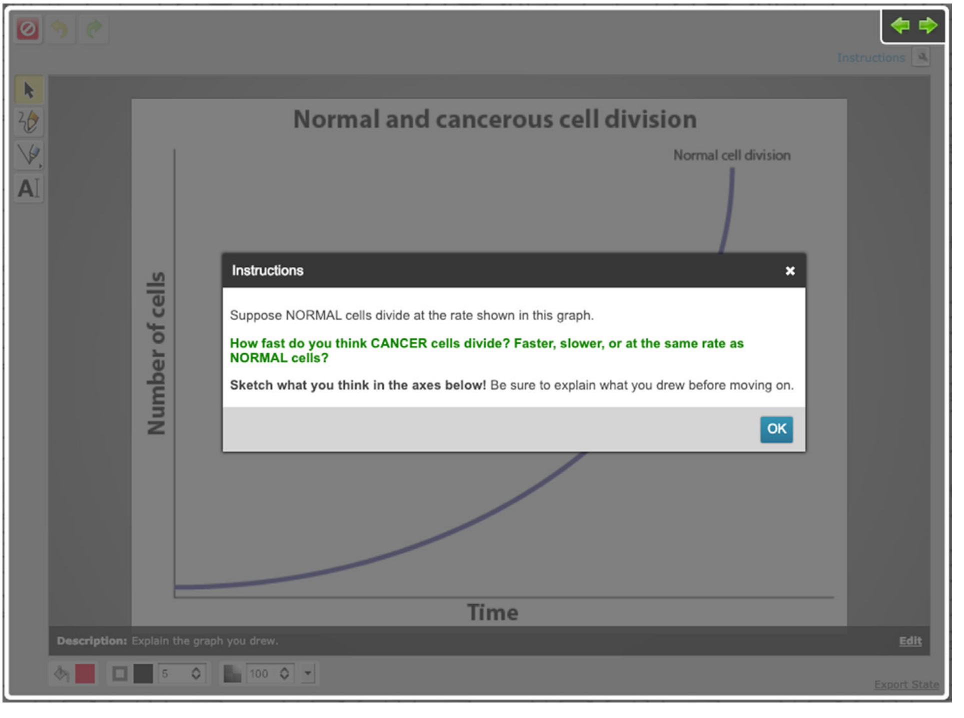


FIGURE 1 The instructions for the first graphing activity, early in the *Mitosis* unit [Color figure can be viewed at wileyonlinelibrary.com]

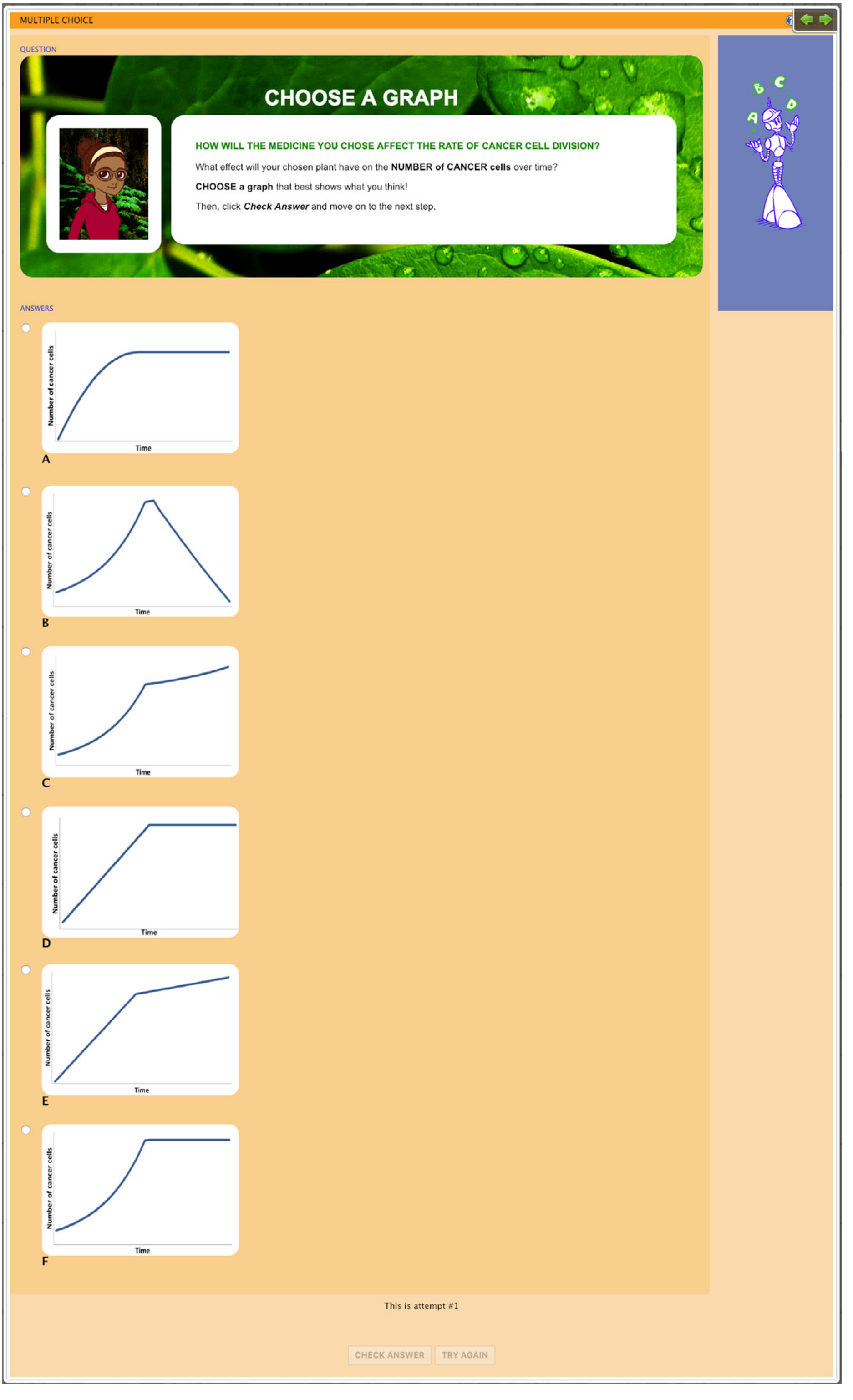


FIGURE 2 The instructions for the second graphing activity, near the end of the *Mitosis* unit [Color figure can be viewed at wileyonlinelibrary.com]

arguments in response to dilemmas. KI items scored using KI rubrics (see below) have been shown to be valid measures of students' conceptual learning (Linn, Lee, Tinker, Husic, & Chiu, 2006; Liu, Lee, & Linn, 2011). They are developed in partnership with education researchers and subject-matter experts to ensure that they adequately represent age-appropriate domain knowledge, and also offer chances for learners to display their understanding. Studies have shown KI items to have satisfactory psychometric properties related to internal consistency, differential item functioning, item fit and discrimination index; and reliability across different WISE units and implementations (Liu, Lee, Hofstetter, & Linn, 2008).

Items 1, 2, 4, and 5 of the pretest and post-test were developed and refined over previous classroom studies with the *Mitosis* unit (Matuk & Linn, 2013; Williams, Linn, & Hollowell, 2008). They addressed key ideas related to the process and purpose of cell division; and to the relationship between cell division, cancer, and cancer treatment. The first of these items assessed students' general understanding of the process of cell division: It asked them to order images of cells in various states of division into chronological order. The second item assessed students' understanding of the purpose of specific processes in cell division: It showed an image of a cell undergoing anaphase, and asked students to describe what is happening inside the cell pictured, and to explain the importance of those events to the cell cycle. Items 4 and 5 assessed students' abilities to integrate their understanding of cell division with their understanding of cancer and cancer treatment. It had students explain which phase of cell division a drug should target to keep cancer growth under control. Together, items 1, 2, 4, and 5 addressed the domain concepts intended to be conveyed by the unit.

Item 3 assessed students' abilities to distinguish among diverse science ideas. It offered a list of known ideas about spindle fibers, and then asked students to select, from among two new ideas, one that would contribute to a coherent explanation for the role of spindle fibers in cell division. In doing so, this item used a topic not explicitly addressed in the unit to determine students' more general ability in a particular aspect of the KI process: distinguishing ideas.

Item 6 was designed for the purposes of this study to assess students' abilities to connect their conceptual understanding of cancer treatment to graph representations of cancer treatment. It asked students to draw a graph to represent the change in numbers of cancer cells before, upon, and after treatment with an effective medicine. This item directly aligned with the graphing activities in the unit, which had students graphically represent cell numbers over time.

3.4 | Analysis

To determine whether students gained greater integrated knowledge following the unit (Research Question 1), we performed a repeated measures t-test to detect significant differences between students' scores on the pretest and post-tests. We used KI rubrics to score the pretest/post-test items (Tables 2–4). Rubrics for items 1, 2, 4, and 5 were refined over multiple previous classroom implementation studies of *Mitosis* (e.g., Matuk & Linn, 2014, 2018; Williams et al., 2008). These rubrics award points to responses based on the number of links between relevant normative ideas (Liu et al., 2008). For example, a student's response received the highest score if, within a coherent explanation, it normatively addressed each of the key ideas targeted by an item; it received fewer points if it addressed fewer of those key ideas, and/or explained them non-normatively.

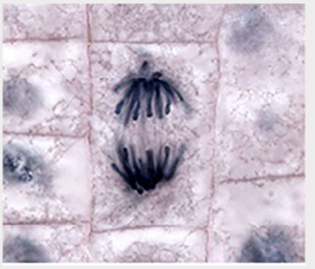
To describe students' conceptual understanding as indicated by their graphs (Research Question 2), we scored the pre-/post-graphing item created for this study by developing a new rubric that gave an holistic score to both the written and graphed components of students' responses (Table 5). Scores

TABLE 2 Rubric for scoring items 2.1 and 2.2 of the pretest and post-test in Study 1 [Color figure can be viewed at wileyonlinelibrary.com]

Item prompt

2.1 Describe what is happening in this cell.

2.2 Explain why the phase pictured above is an important part of the cell cycle.



Key ideas

- Anaphase is identified as the phase pictured.
- The actions of the cell's organelles are described (i.e., the cell's chromosomes are being halved and pulled by spindle fibers to opposite sides of the cell).
- The purpose of the organelle's activity is explained (i.e., each new cell must have identical DNA).

Scoring rubric and examples

Score	Criteria	
0	No answer	(Blank)
1	Off-task or uninterpretable	I do not know.
2	Irrelevant, incorrect, or ambiguous ideas	The cell is dividing. Because when you cut yourself the cell can heal your hurt.
3	Partial understanding. One normatively stated key idea, or two partially correct key ideas	The cell is going through anaphase. This happens when the cell is separating into two new cells. This phase in mitosis is important because if not with this, the cells is technically still one cell.
4	Fair understanding. Two normatively stated key ideas.	The cell is in the anaphase stage. This is when the cell's daughter chromosomes move away from each other to opposite ends of the cell. This phase is important because at this stage the cell is in the process of dividing.
5	Complete understanding. Three normatively stated key ideas	The cell is undergoing mitosis in the phase of anaphase. Anaphase is when the cell's spindal fibers are pulling toward the centrioles and getting copies of the chromosomes. If there was not anaphase, then the cell's would not have an exact copy of the DNA therefore preventing the nucleus how to build the cell parts. Without the cell parts, the cell would not be able to function and die.

were based on three criteria: (i) coherence between the graph and its accompanying written description: That is, what the student described in words is also reflected in their graph, and vice versa; (ii) a complete narrative is communicated about the effects of cancer treatment, including a description or representation of before, at the moment of, and after treatment; and (iii) the response as a whole demonstrates an understanding that cancer medication decreases the number of dividing cells. The highest scoring responses were those that connected changes in the graph's shape to an explanation of the process of cancer treatment.

Two raters independently and iteratively coded subsets of the data and resolved disputes through discussion until they had reached a Cohen's kappa of 0.66. This is considered to be good agreement (Fleiss, 1981). Given the manageable amount of data, we proceeded through social moderation (Frederiksen, Sipusic, Sherin, & Wolfe, 1998; Herrenkohl & Cornelius, 2013): One rater took the lead in scoring the rest of the responses, and the second rater verified them for further disagreements, which were again resolved through discussion.

TABLE 3 Rubric for scoring item 3 of the pretest and post-test in Study 1

Item prompt

Anjali and Renaldo want to explain why SPINDLE FIBERS are important in cell division. They begin by listing important ideas to include in their explanation.

Here are their ideas:

- Normal cell division results in two daughter cells with equal numbers of identical chromosomes.
- Spindle fibers pull the chromatids toward opposite ends of the cell.
- During mitosis, a cell's chromatids line up along the middle of the cell.
- Genetic mutations happen when cells do not have normal numbers of chromosomes.
- Spindle fibers attach to the chromatids.
- Spindle fibers extend from the cell's centrioles toward the middle of the cell.

Anjali and Renaldo decide they need more information to write a GOOD explanation. They ask their classmates for ideas.

1. Which of these NEW ideas should Anjali and Renaldo add to their list?
   - Genetic mutations can cause diseases and other health problems.
   - Spindle fibers pull the chromatids to opposite ends of the cell during anaphase, the third phase of mitosis.
2. How will this NEW idea help Anjali and Renaldo better explain the importance of spindle fibers, than if they only used their own ideas?

Key criteria

- If student chooses the "spindle fibers" idea, he/she explains that it adds information about when (i.e., the phase) in the cell cycle the spindle fibers pull chromatids apart.
- If student chooses the "genetic mutations" idea, he/she explains that it adds information on how diseases and other health problems can be a consequence of genetic mutations.
- Student notes that the idea is not already present among the existing ideas.
- Student notes that the new idea complements the existing ideas to create a more complete explanation.

Scoring rubric and examples

Score	Criteria	Examples
0	Blank	[No response given]
1	Incomprehensible or off-task	• Anjali and Renaldo explain connect like a bridge • If your spindle fiber crack than you can get cancer or other diseases
2	Rephrases the question without answering it. Circular reasoning, repeats the question (because it is a better or more useful/helpful idea). In addition the response does not link 2+ ideas.	• It will help them by making it easier for them. • Spindel fibers pull the chromatids to opposite sides off the cell [*Rephrases a portion of the idea without mentioning the new information*]
3	Says THAT the new idea adds information about spindle fibers and/or their importance WITHOUT specifying what information is added. May or may not link any 2+ ideas together, and neither of these are one of the newly added ideas.	• The new idea will help Anjali and Renaldo because it gives them an idea of spindle fibers. • It will help them because they pull apart and it is using detail of what phase it is going through
4	States *what* new information is added OR links 2+ ideas. Depending on the idea chosen: (1a) Says that the new idea *adds information/details* about the specific *phase* (anaphase). Also acceptable if instead of saying "anaphase," the response alludes to the timing of the event in the context of the cell cycle. (1b) Says that the new idea *adds information/details* about the consequences of genetic mutations (i.e., health problems, disease). OR (2) Links any 2+ ideas together, one of which must be the newly added idea (must state anaphase).	• This new idea will help them better explain because the idea tells what happens during anaphase and how each daughter cell gets the same amount of DNA in them and how each cell splits.
5	States *what* new information is added AND links 2+ ideas. Depending on the idea chosen: (1a) Says that the new idea *adds information/details* about the specific *phase* (anaphase). Instead of saying "anaphase," the response may allude to the timing of the event in the context of the cell cycle. (1b) Says that the new idea *adds information/details* about the consequences of genetic mutations (i.e., health problems, disease). AND (2) Links 2+ ideas together including the newly added idea.	• The new idea says that the fibers pull the chromatids to opposite sides of the cell in anaphase. This helps explain when the fibers work to help each daughter cell gets the same number of chromosomes. (has 1a and 2)

TABLE 4 Rubric for scoring item 4 of the pretest and post-test in Study 1

Item prompt

"Explain the effect your drug would have on the different parts of the cell in that phase, and how this would help keep cancer growth under control."

Key ideas

- Identifies a cell *organelle* to be affected by the drug (e.g., nucleus, spindle fibers)
- Explains the *process* by which the drug will interfere with the affected organelle's function (e.g., will prevent spindle fibers from pulling chromosomes apart).
- Refers to the *need* to stop cell division in order to treat cancer.

Scoring rubric and examples

Score	Criteria	
0	No answer	(Blank)
1	Off-task or uninterpretable	I do not know.
2	Irrelevant, incorrect, or ambiguous	This is the first phase of mitosis when the cell begins to change so if you drug this part it can go back to interphase. (*Organelle = N/A; Process = N/A; Need = N/A*)
3	Any ONE of the three key ideas is correctly explained.	I would stop the division at this phase because you can start from early on. If you stop the division to late then the cell would be mutated and a useless cell. (*Organelle = N/A; Process = N/A; Need = Stop division*)
4	Any TWO of the three key ideas are correctly explained.	I think the drug would stop cancer from developing because the cell is about to divide and the spindle fibers are still outside of the centrioles, so the drug would destroy the spindle fibers and prevent the daughter cells from ever going through mitosis. (*Organelle = spindle fibers; Process = N/A; Need = prevent daughter cells from undergoing mitosis*)
5	All THREE key ideas are correctly explained.	This would help keep caner growth under control because this is the phase during mitosis, which makes it a great time to stop from dividing. It has not fully developed to divide, but at the same time it is past the previous steps. In mitosis, the chromosomes line up in the middle to prepare to divide, but if they stop it when the spindle fibers are still attached to the chromosomes, it will stop the cell from reproducing. It will effect the chromosomes, the spindle fibers, and DNA. This is because chromosomes include DNA, so all the information will not get anywhere. Also the chromosomes will be effected because the drug is stopping it is process of dividing into two. Finally, the spindle fibers will get effected because it cannot pull the halved chromosomes apart. (*Organelle = chromosomes, spindle fibers, DNA; Process = dividing in two; pulling chromosomes; Need = stops chromosomes from being divided*)

3.5 | Findings

3.5.1 | Students' gains in understanding (Research Question 1)

Our analysis suggests that the unit was successful in building students' integrated understanding of the science underlying cancer treatment: All students gained from the pre ($N = 28$, $M = 1.4$, SD $= 0.6$) to the post-test ($N = 26$, $M = 2.7$, SD $= 0.6$), with overall gains being significant ($t[29] = 10.97$, $p < 0.0001$, $M = 1.27$, SD $= 0.64$; Figure 3). The effect size of this result ($d = 2.17$) exceeded Cohen's (1988) standard for a large effect size ($d = 0.80$).

3.5.2 | Students' changing understanding as revealed through their graphs (Research Question 2)

Closer analysis of individual pretest responses to the graphing item showed that many students initially produced the linear ($n = 8$, Figure 4) and discrete ($n = 4$, Figures 5 and 6) graphical forms familiar from their prior mathematics courses, rather than the curved graphs expected given the axes with which students were provided. (Most of the other students' graphs were either blank or

TABLE 5 Scoring rubric for the pretest and post-test graphing item for Study 1 [Color figure can be viewed at wileyonlinelibrary.com]

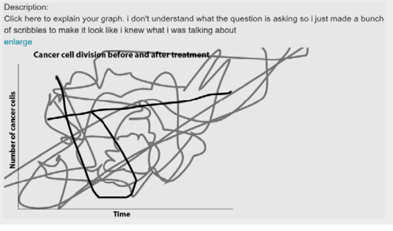
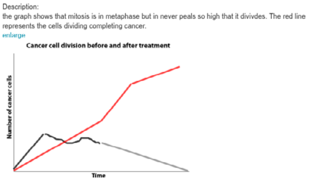
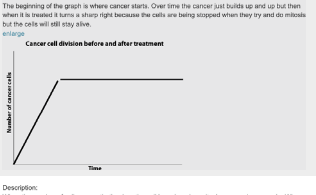
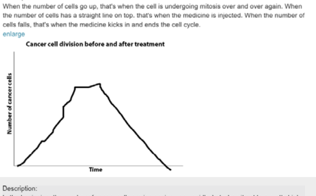
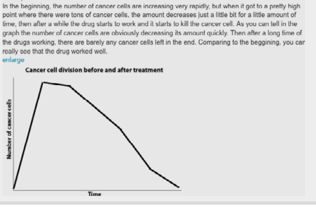
Item prompt
How will your drug affect the NUMBER of CANCER CELLS in the body over time?
Will cancer cells increase in number? Will they decrease? Will they stay the same?
DRAW a GRAPH to show what you think!
Make sure your graph shows how cancer cell numbers change over time:

1. BEFORE treatment;
2. WHEN the drug is first taken;
3. AFTER the drug has been working for some time.

When you are done, DESCRIBE and EXPLAIN your graph in the space below. Then, move on to the next step.

Criteria

1. *Coherence*: The graph and its accompanying written description communicate the same pattern.
2. *Narrative*: The effects of cancer treatment on cell numbers before, during, and after treatment are clearly indicated in writing and/or through annotations on the graph.
3. *Understanding:* The response as a whole demonstrates an understanding that an effective cancer treatment decreases the number of dividing cells.

Score	Example	Explanation
0		No response is given.
1		Off task or uninterpretable. The response does not address the question, or does not include enough information to be reliably interpreted by raters.
2		May address some or all of the criteria, but none are normative. The *coherence* between the graph and the written explanation is tenuous as the terms "peals" and "completing cancer" have little sense alone, nor in relation to the graph. The graph's black line may represent a narrative of cell numbers before, during and after treatment, and additionally, an *understanding* of how cell numbers should decrease upon treatment. However, this is not clearly indicated. as well, the juxtaposition of the red line suggests that the student has confused narratives of different processes on the same graph
3		At least one of the criteria is met. The written description *coheres* well with the graph. However, the *narrative* describes only the events before and during treatment. There lacks an *understanding* of how cell numbers should decrease after treatment.
4		At least two of the criteria are met. The graph and written description *cohere* well. A *narrative* describes the number of cells before, during, and after treatment. However, the written description remains literal, and it is not clear that the student *understands* that an effective cancer treatment must result in cell numbers decreasing.
5		All the criteria are met. The graph and description *cohere* and convey a narrative of cell numbers before, during, and after treatment. As well, the written description conveys a conceptual *understanding* that for the medicine to "work well," it must cause the number of cells to decrease.

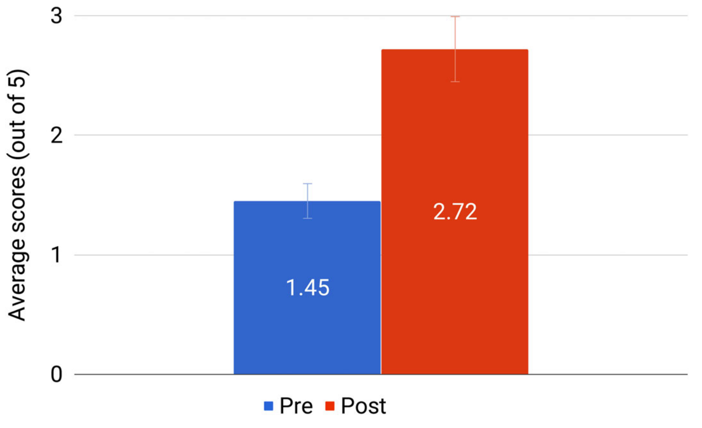


FIGURE 3 Overall average pre and posttest scores for Study 1 [Color figure can be viewed at wileyonlinelibrary.com]

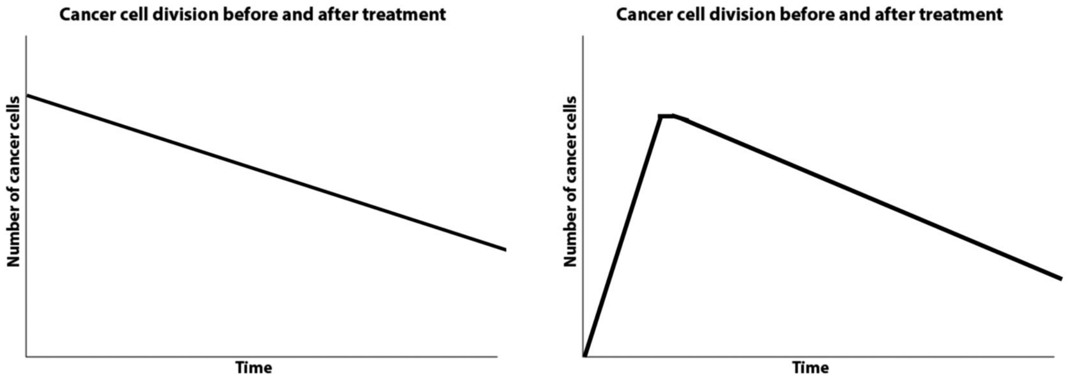


FIGURE 4 An example of one student's Level 2 pretest response (left) is accompanied by the description: "The nunmber [sic] of cancer cells will decrease." The same student's Level 5 posttest response (right) is accompanied by the description: "At the beginning the cancerous cells are many and the numbers climb but then after treatment the numbers slowly decline." It shows how the acquisition of a more complex graphical language was accompanied by a more complete narrative explanation of the process

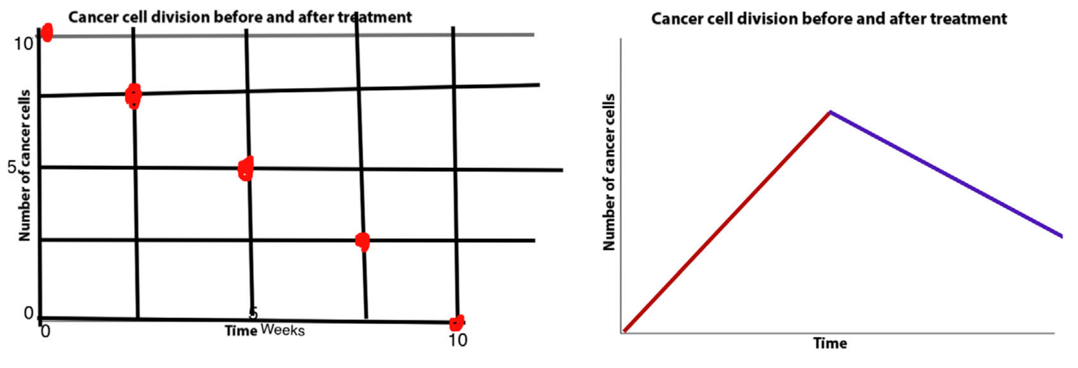


FIGURE 5 An example of one student's Level 2 pretest response (left), and Level 5 posttest response (right). Initially, this student drew a grid and plotted points at specific coordinates to quantify the decrease in cells. This graph is accompanied by the description: "As the weeks go down, the caner cells decrease.?" Afterward, this student used several linear functions to build one piecewise function that captures a more complete picture of the process before, during, and after treatment is administered. This posttest graph is accompanied by the description: "The red line shows how cells infected with cancer will increase without the drug. The purple like [sic] shows how the number of cancer cells will decrease when the drug is taking place." [Color figure can be viewed at wileyonlinelibrary.com]

uninterpretable.) While these graph forms demonstrate students' understanding that effective cancer medication should decrease the number of cancerous cells, they leave it ambiguous as to whether students truly grasped the continuous nature of cell division.

We also found that students gained an appreciation for the continuous nature of cancerous cell division under treatment, and an ability to graphically express the effects of cancer treatment on the rate of cell division. Specifically, none of the graphs that students generated on the post-test were discrete graphs, as they were at the pretest. Moreover, only three students generated linear graphs by the post-test. Meanwhile, as many as 13 students generated piecewise representations (Figures 4 and 5) and 10 students generated curved representations (Figure 6). These results show that all students ultimately came to generate graph forms that more appropriately represent the continuous nature of cancer treatment.

Our analysis furthermore shows how particular graph forms may both limit and enable students in expressing their conceptual understanding. For example, students who initially used linear or discrete graphs typical of their mathematics courses generated incomplete narratives of the process; they described only the decrease in numbers of cells, or else, the states before and after treatment. By their post-tests, however, these students no longer used grids, nor even marked numbers on their graphs' axes. Instead of adhering to such formal conventions, these students now sketched qualitative graphs to illustrate complete narratives of the complex and continuous process of cancer treatment. Thus, students developed fluency with qualitative graphs, and gained competence in using these to convey their conceptual science understanding of the process and effects of cancer treatment.

4 | STUDY 2

4.1 | Integrating graph construction and critique into *Mitosis*

Findings from Study 1 illustrated the value of qualitative graphing activities for enabling students' to integrate their conceptual understanding of mitosis and graphing to produce narrative explanations of cancer treatment. During the following academic year, we conducted a second study to further refine our understanding of how the design of graphing activities can impact students' learning. Specifically,

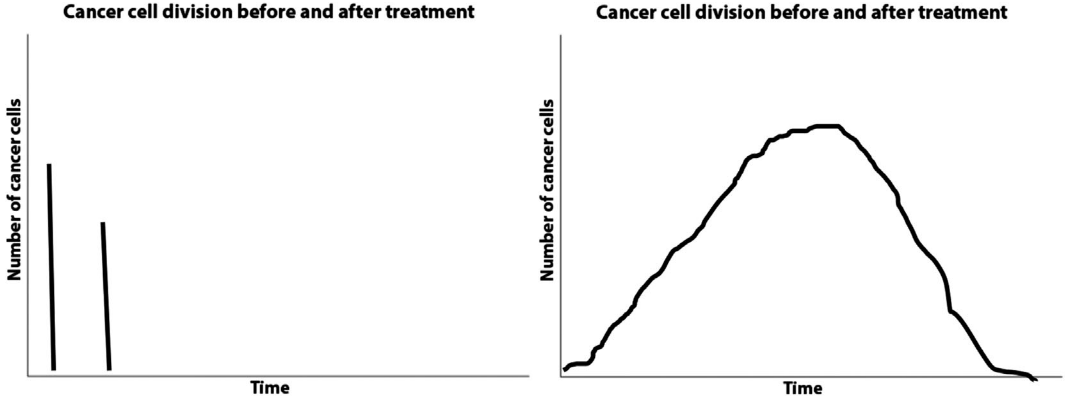


FIGURE 6 An example of one student's Level 2 pretest response (left), and Level 4 posttest response (right). Initially, the student generated two lines, one longer and one shorter, presumably to illustrate a greater number of cells before, and a smaller number of cells after treatment. In the post-test, this student used a curve, accompanied by the description: "cancer will increase the cells but right as the drug works it the decreas. [sic]." This posttest response demonstrates a more accurate conception of the continuity of events

we sought to determine: (i) How are students' abilities to integrate their understanding of graphs and science revealed through graph construction and critique activities embedded in inquiry contexts? (ii) What is the relative impact of critiquing and constructing qualitative graphs on students' pretest and post-test graph learning gains? and (iii) what are teachers' perspectives on the value of graphing in an inquiry learning context? As reviewed above, each of critique and construction are both critical to metarepresentational competence. Yet, their roles in promoting science inquiry learning within qualitative graphing activities remains underexplored.

To create a rich context within which to explore students' critique and construction of qualitative graphs, we expanded the *Mitosis* unit to introduce surgery and chemotherapy as typical cancer treatments. In doing so, we wanted to create a dilemma (in this case, the choice between surgery and chemotherapy) that would require students to draw on their science understanding to justify a solution, and offer an opportunity to express their solution through qualitative graphing. In our chosen case, each of surgery and chemotherapy come with trade-offs: Surgery can quickly remove cancerous cells, but risks damaging healthy organs. In addition, any remaining cancerous cells will continue to divide, which may lead to a return of the disease. Meanwhile, chemotherapy avoids the risks of surgery, but because it targets all rapidly dividing cells—not just cancerous cells—chemotherapy is also accompanied by side effects such as nausea and hair loss. Knowing that neither treatment is perfect, students are challenged to design cancer treatments that maximize the effects on cancerous cells while minimizing damage to healthy cells.

We added this challenge as a culminating activity within the *Mitosis* unit, and created two versions (Figure 7). In one version of the unit (*Construct*), students were prompted to prescribe and explain a treatment plan for a cancer patient, and to draw a graph on given axes to show the effects of their treatment on the numbers of cancerous cells over time. In the other version (*Critique*), students were given a graph of the effects of a fictional 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. By doing so, we aimed to direct students' focus toward interpreting the meaning of the given graph, and to evaluating the argument they interpret in light of their conceptual understanding of cancer and cancer treatment. In both versions of the unit, students then shared their graphs and explanations and commented on the work of their peers through an online discussion forum. They were then instructed to use their peers' ideas to revise their work. Together, these

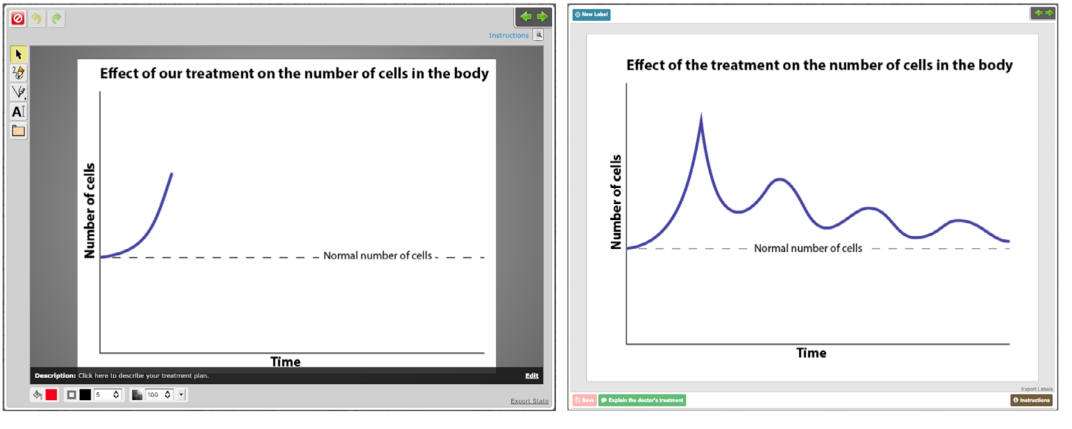


FIGURE 7 The *Construct* (left) and *Critique* (right) activities in the two versions of the *Mitosis* unit used in Study 2 [Color figure can be viewed at wileyonlinelibrary.com]

activities were intended to create equally rich opportunities for students to articulate their ideas about the effects of cancer treatment through qualitative graphing. By comparing students' performance between critiquing and constructing qualitative graphs, we aimed to explore the value that each might add to supporting students in building an integrated science understanding.

4.2 | Participants and study design

4.2.1 | The *Mitosis* unit

Participants were 117 grade 7 students across four class periods, all taught by one teacher (a colleague of the teacher in Study 1), and from the same middle school as in Study 1. As in Study 1, students worked in pairs on shared computers for approximately 10 consecutive days to complete the unit. On the first and last days, they completed the same pretest and post-test from Study 1 that assessed their understanding of the science content. The teacher, who had 8+ years of experience teaching with WISE, and who had taught previous versions of *Mitosis* when these did not include graphs, intentionally coordinated her instruction with that of her colleague from Study 1. Thus, she similarly 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. To compare the value of constructing and critiquing graphs (Research Questions 1 and 2), the teacher formed student pairs, and randomly assigned half within each of her four class periods to complete one of either the *Construct* or *Critique* versions of the unit.

4.2.2 | Teacher interviews

To gather teachers' perspectives on their students' performance with the graph construction and critique activities (Research Question 3), we conducted approximately 30-min long individual phone interviews with the two teachers shortly after they had enacted their versions of the unit. One teacher was interviewed twice: Once following Study 1, and again following Study 2. Due to technical issues that prevented her students from completing the graph drawing activity, her classes' data was not included in Study 2. A second teacher was interviewed once following her enactment of the unit in Study 2. Within our larger research and development program, an overarching goal of these interviews was to gather information to more generally improve the pedagogical and technological design of the WISE platform and its units. For the purposes of this research, we focused our analysis of these interviews on one set of open-ended questions, designed to probe teachers' impressions of the graphing activities' impacts on students' learning (e.g., Please comment on how your students' managed with the graphing activities. What kinds of questions did your students ask? What issues did they encounter? What guidance did you offer them? How might you improve these activities for the next time?). We also used these interviews to gather information about the instructional context and how teachers supported their students' graphing activities; and to triangulate with, and strengthen the validity of our analyses of students' learning (Cypress, 2017; Morse et al., 2002).

4.3 | Data and analysis

4.3.1 | Analyzing students' graphing abilities from in-unit construction and critique activities (Research Question 1)

To understand how graph construction and critique demonstrate students' abilities to integrate knowledge of graphing and science, we examined students' responses to the graphing activity embedded within the unit. These responses included the graphs that *Construct* students generated along with their accompanying explanations, and the annotated graphs and accompanying explanations from the *Critique* students. They were moreover students' initial graphs and explanations, that is, those generated prior to them commenting on their peers' work and revising their responses.

The rubric we developed to score these within-unit graphs and explanations was designed to rate students' abilities to integrate science content understanding with graphing abilities (Table 6). This rubric identified the presence of several key criteria in their responses, including: (i) an explanation that connected science content learned in the unit (e.g., what cancer is, how cells divide, how chemotherapy works) to the graph, as opposed to a literal description of the graph; (ii) a sense of the imperfections or trade-offs of cancer treatment, as opposed to the belief that treatment is a straightforward and uncomplicated solution; (iii) a recognition that to mitigate side effects, the treatment could be given in multiple brief cycles rather than in a single dose; (iv) 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.

This rubric also rated the accuracy of students' responses. 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 worth a possible total of 10 points. This score captures the overall quality of responses in terms of students' abilities to integrate relevant science content and graph features in their critiques or constructions of graphs.

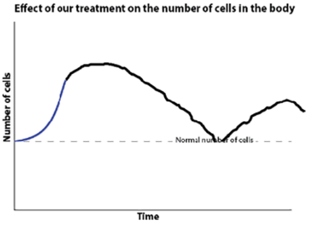
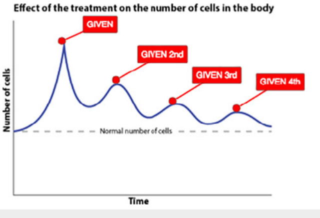
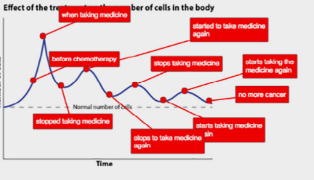
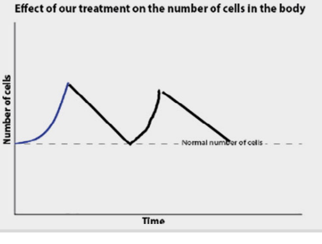
4.3.2 | Analyzing the impacts of critique versus construction on students' graph learning gains (Research Question 2)

To understand how critique and construction impacted students' graph learning, we analyzed their gains on the graphing item of the pretest and post-test. The pretest and post-test consisted of the same five items from Study 1, which together 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). As explained in Study 1, the graphing item had students generate and explain a graph of the number of cancer cells before, during, and after a proposed treatment. We used the same rubric described in Study 1 to also score responses from Study 2 participants (Table 5). Two raters independently scored portions of the responses, resolved disputes, and refined the rubric through discussion. Inter-rater reliability was excellent (Fleiss, 1981), with Cohen's kappa values between 0.79 and 1 across categories.

4.3.3 | Analyzing teachers' interviews (Research Question 3)

We used qualitative description (Miles, Huberman & Saldaña, 2014; Sandelowski, 2010) to analyze recordings of, and notes taken during teachers' interviews. To complement findings on students' learning through their graphing activities, this analysis focused on how teachers' viewed the graphing activities to support the broader science learning goals of the unit. Our analysis also focused on teachers' impressions of the differences they perceived in students' learning between the current unit, and the previous versions of the unit that did not include graphing activities. We triangulated teachers' comments with other findings to offer a more holistic picture of the impacts of the graphing activities on students' learning.

TABLE 6 Rubric for scoring the presence or absence of key criteria in students' responses from Study 2 [Color figure can be viewed at wileyonlinelibrary.com]

Criteria	Explanations and examples
1. Content-based explanation	Explanation: Uses relevant science content to interpret the graph. *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.
2. Sense of trade-off	Explanation: Understands that cancer treatment involves a trade-off that can lead to side effects. *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.
3. Treatment cycles	Explanation: Uses/recognizes an approach to treatment that mitigates risks and side effects. *Critique* The doctors gave it to her multiple times to kill off the cancer cells...  *Construct* When the number of cells reach the climax she takes not that much medicine. It will go down but star rising again so she would take the medicine when it starts rising again. 
4. Narrative description	Explanation: Conveys the process of treatment by identifying sequences of events, and recognizing the change in cell numbers over time. *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 will not go below normal. 

Sources of examples (i.e., from the *Critique* or *Construct* groups) are indicated in italics.

4.4 | Findings

4.4.1 | How do construction and critique reveal students' abilities to integrate graphing and science knowledge (Research Question 1)?

Students appeared to be more successful at critiquing graphs than at constructing graphs. Those students who critiqued a given graph of the cancer treatment's effects had significantly higher overall scores on this in-unit activity ($N = 29$; $M = 9.59$; SD $= 1.05$) than students who constructed graphs

($N = 32$; $M = 8.63$, SD $= 1.39$), $t(59) = 3.03$, $p < 0.005$, $d = 0.79$). This result approaches high practical significance, as suggested by Cohen's effect size ($d = 0.79$).

Meanwhile, we found certain group differences in the presence of key criteria, as shown by a 2 x 4 chi-square test, $x^2(2) = 21.31$, $p < 0.0001$ (Figure 8). Specifically, *Critique* students ($N = 29$, $M = 0.97$, SD $= 0.19$) were more likely than *Construct* students ($N = 32$, $M = 0.19$, SD $= 0.40$) to identify the importance of repeated doses of medicine, $t(59) = 9.64$, $p < 0.0001$. This result had a large effect size (Cohen $d = 2.49$), and might be explained by the fact that *Critique* students, who were provided with a graph, had only to identify these features on that graph; meanwhile, *Construct* students, who generated their own graphs, were left to discover this strategy on their own and did not always do so successfully.

Critique students ($N = 29$, $M = 1.00$, SD $= 0.00$) were also more likely than *Construct* students ($N = 32$, $M = 0.44$, SD $= 0.50$) to describe the narrative process represented by the graph, $t(59) = 6.01$, $p < 0.0001$, a finding that has high practical significance (Cohen $d = 1.58$). Being given an already constructed graph may have allowed *Critique* students to focus on developing narrative descriptions of it. Meanwhile, the effort required to construct a consensus graph may have led *Construct* students to put less effort into their accompanying 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 $= 0.45$), $t(59) = 2.06$, $p < 0.05$. While this result has a moderate effect size (Cohen $d = 0.52$), it suggests that constructing graphs may have encouraged students to more deeply consider their graphs' conceptual meaning.

4.4.2 | What is the relative impact of constructing versus critiquing graphs on students' graph learning (Research Question 2)?

Students from both conditions made significant gains on the graphing item from the pre ($N = 117$, $M = 1.99$, SD $= 2.79$) to the post-test ($N = 117$, $M = 7.42$, SD $= 2.59$), $t(232) = 15.41$, $p < 0.0001$, $d = 2.02$). A t-test comparing the mean gains between conditions found that *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 $= 4.02$) from the pretest to the post-test. These findings suggest that in spite of group

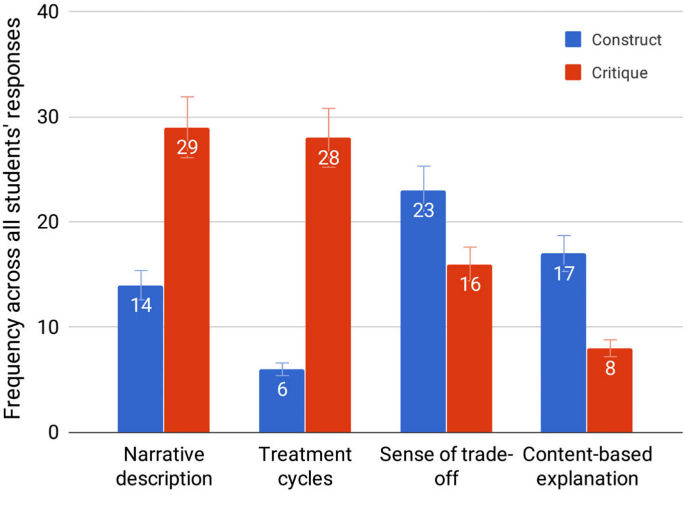


FIGURE 8 Construct and *Critique* students differed significantly in the frequencies of narrative description, treatment cycles, and content-based explanations on the graphing item embedded in the unit [Color figure can be viewed at wileyonlinelibrary.com]

differences in performance within the unit, each of the construct and the critique activities helped students to improve their abilities to articulate key ideas, as well as to express these ideas normatively in both written and graphic forms.

Some group differences that were apparent within the unit persisted to the post-test. Specifically, *Critique* students ($N = 55$, $M = 0.24$, SD = 0.47) were more able than *Construct* students ($N = 62$, $M = 0.08$, SD = 0.27) to identify the importance of cycling treatment, as shown by their greater pretest to post-test gains on the graphing item, $t(115) = 2.22$, $p < 0.05$. While this result represents a low to moderate effect size (Cohen $d = 0.42$), it is consistent with the greater ability of *Critique* students than *Construct* students on the activity embedded in the unit, to recognize the importance of repeated doses of a drug. Meanwhile, *Construct* students made significantly greater pretest to post-test 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), $t(115) = 2.52$, $p < 0.05$). This result approaches moderate practical significance (Cohen $d = 0.42$), and is consistent with *Construct* students using more science content ideas within the unit to explain their graphs than *Critique* students. Together, these findings suggest that while critique activities appeared to support students in identifying and interpreting important patterns from graphs during the unit, construction activities better prepared students to integrate their science and graphing ideas beyond the unit. These findings suggest that in different, but equally valuable ways, both critique and construction activities can improve students' abilities to integrate graph and science ideas.

Closer inspection of students' responses offered examples of the challenges students experienced with using graphs to explain cancer treatment. By the end of the unit, some students' written and graphed responses demonstrated a more integrated understanding of the cancer treatment process (e.g., Figure 9). Other responses reflected difficulties with graphs consistent with other researchers' observations (e.g., Lai et al., 2016). For example, with the exception of two student pairs—one in each treatment group—students described the visual features of their graphs without interpreting these in the context of the science (e.g., “The treatment started, stopped, started again… This made the number of cells go up and down…”). 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” (Workgroup ID 218836).

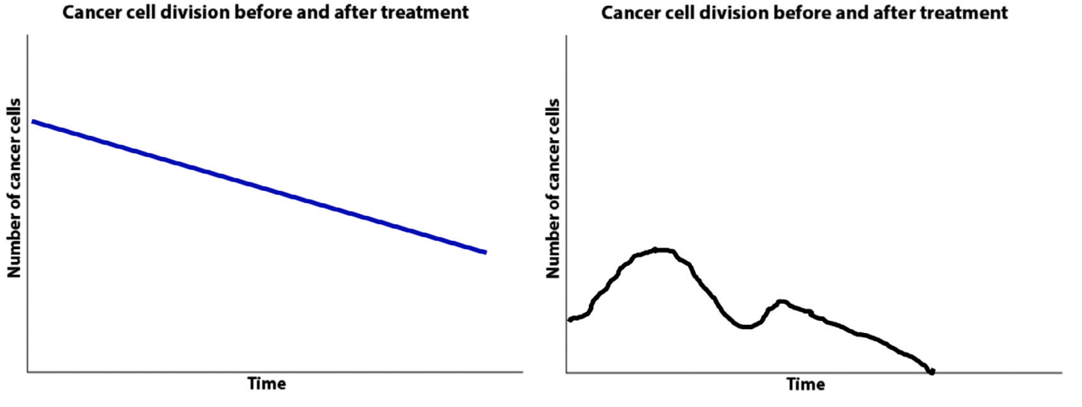


FIGURE 9 Left: One student's pretest response, which conveys a simplistic understanding of the effect of the medicine, along with the explanation: “The drug will stop the cells from multiplying…” right: The same students' posttest response with the accompanying explanation: “My graph… is supposed to 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.” (Workgroup ID 92037) [Color figure can be viewed at wileyonlinelibrary.com]

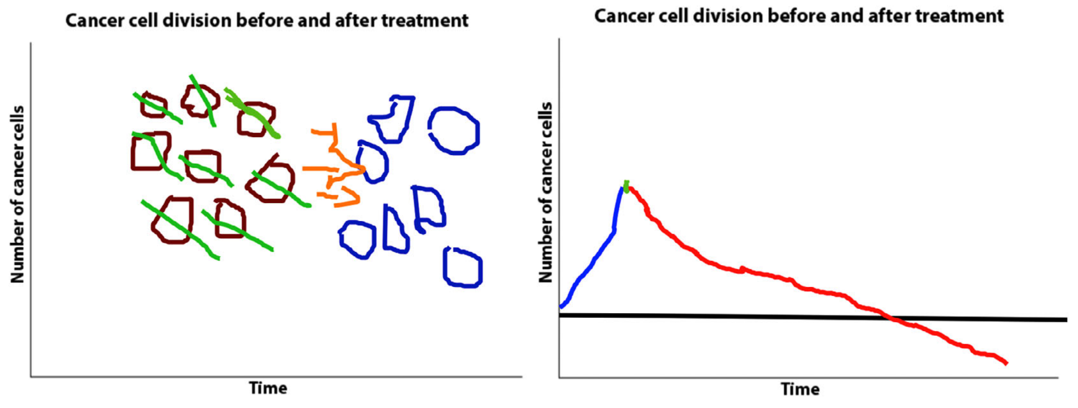


FIGURE 10 Left: One *Critique* student's pretest response showing a pictorial representation of the cancer treatment process. The graph is accompanied by the explanation: "The red circles are cancer cells. My drug is represented by the green lines crossing them out, then them turning them into regular 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." (Workgroup ID 89152) [Color figure can be viewed at wileyonlinelibrary.com]

While most students left their pretests blank, a few students created pictorial representations of the effects of cancer treatment (Figure 10); or graphed an increasing linear function (Figure 11). In each of these cases, the students improved their responses by the post-test. 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 post-test (drawing a series of graphs as opposed to a single one, and depicting rising linear functions in spite of the actual trend; Figure 12).

4.4.3 | What are teachers' perspectives on the value of graphing in science inquiry contexts (Research Question 3)?

Interviews from the two teachers who taught this and other versions of the unit broadened our perspective on our findings regarding the value of the graphing activities. The teacher in Study 1, for example confirmed that the graphing activities added value to her students' learning. She reported observing that

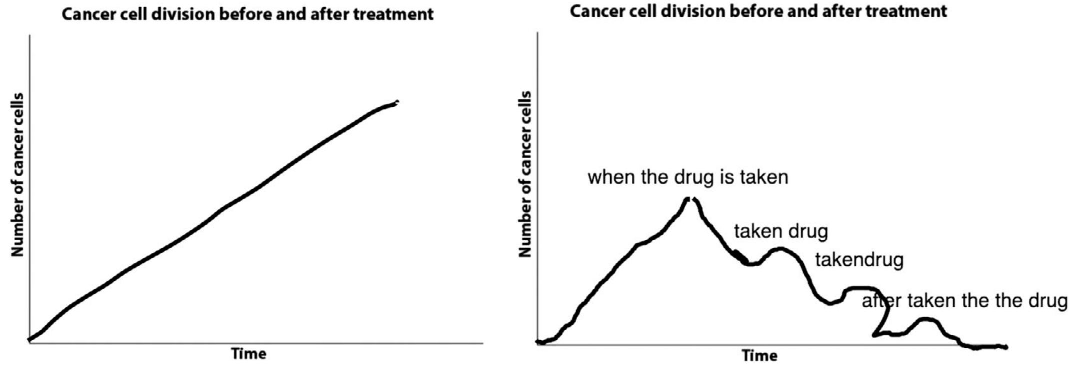


FIGURE 11 Left: One *Critique* student's pretest response, showing a rising linear function, and the same students' posttest response (right), demonstrating a more accurate narrative of the treatment process and the cycling of doses of medicine (Workgroup ID 92399)

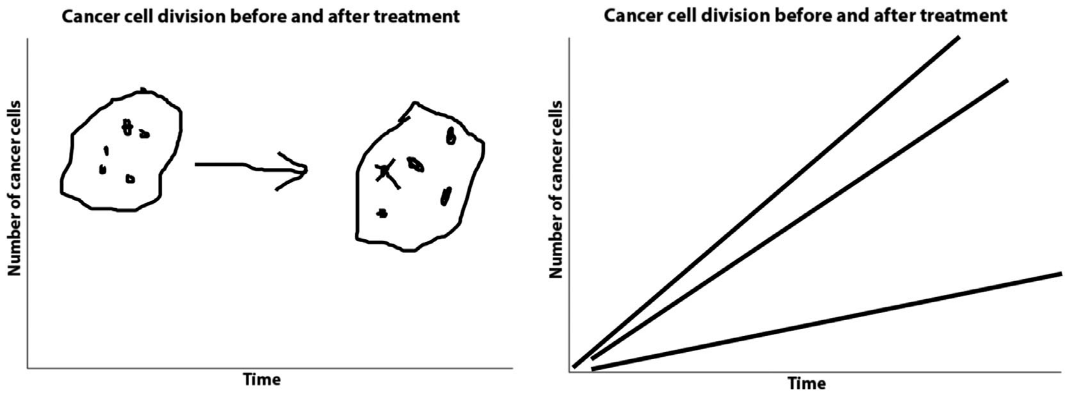


FIGURE 12 Left: One *Construct* students pretest response, showing a pictorial representation of cancer cells before and after treatment, and the same student's posttest response, which incorrectly uses a series of rising linear functions to represent the numbers of cancer cells before, during, and after treatment (Workgroup ID 91962)

her students better understood certain key ideas compared to her students in prior years, who used versions of the unit that did not include graphs. Specifically, students appeared better able to grasp the idea that cancer medicine should stop cells from dividing, and the teacher guessed that this was because the graphs offered a visual representation of that process. However, this teacher also noted that the graphing activity was challenging for those of her students who were not strong in mathematics. Although qualitative graphing, in contrast to quantitative graphing, does not require number manipulation, it is conceivable that any kind of graphing activity may provoke math anxiety among certain students. Other research has found math anxiety to be related to memory and academic performance (Carey, Hill, Devine, & Szücs, 2016; Dowker, Sarkar, & Looi, 2016; McDonough & Ramirez, 2018). Qualitative graphing moreover requires a degree of visual–spatial thinking ability that is also associated with mathematical ability, and that can vary across individuals (e.g., VanderPlas & Hofmann, 2016). Thus, this teacher's observations suggest that further investigation of individual differences in qualitative graphing may inform ways to strengthen scaffolds for different students (e.g., by altering the way the activity is framed to students).

In contrast, the teacher from Study 2, who had also taught with the version of *Mitosis* from Study 1, noted that her students struggled to understand the connection between the graphing activities and the underlying science. At the time, she noted that cell division was not a typical content topic in students' other school-based graphing activities, and wondered whether this contributed to their confusion. However, she did not repeat this comment following her use of the second version of *Mitosis.* This may suggest that the incorporation of surgery and chemotherapy as a graphing context improved the unit's connection between graphing and science. It may also mean that the teacher had developed more effective strategies for teaching with it. We observed, for example, that on noticing her students struggling with the graphing activities early in the unit, this teacher conducted opener activities that modeled productive strategies. In one opening discussion, for example, the teacher drew four different graphs on the board, and led a discussion with her students about why each might or might not represent cancer growth. She guided students' choice by asking them which they would eliminate, based on what they know. She also had them invent numbers for the axes, although noted that this generally posed even greater challenges to students. Nevertheless, she reported this to have been "an interesting discussion." Moreover, her guidance likely helped to prepare her students to better perform the graph critique and construction activities later in the unit.

These findings suggest that greater thought is needed to more seamlessly integrate graphing into authentic science inquiry investigations, such that the synergy between graphs and science is as apparent to teachers and learners as it is to professional scientists. They also suggest that much remains to be learned about the role of teachers in complementing science-integrated graphing activities.

5 | CONCLUSIONS AND DISCUSSION

This article illustrates opportunities for supporting students in integrating graph and conceptual science understanding within an authentic, social-practice oriented context on the topic of cancer treatment. Study 1 described the introduction of qualitative graphing activities into an existing web-based unit, and found that it improved students' abilities to explain complex scientific processes in both graphical and written forms. Before the unit, students tended to rely inappropriately on simple linear and discrete representations—likely familiar to them from prior, more traditional graph instruction—to reason through the science problems posed. By the post-test, both students' graphs and their written explanations reflected more integrated understanding of cancer as a changing and continuous process. Being introduced to new kinds of graphs through the unit appeared to help students to use these as tools to articulate more integrated science understandings. Even after this brief exposure, students demonstrated an ability to generate and explain graphs in a science context; to express hypotheses through graphs about the impacts of medical interventions on biological processes; and to describe graphs as stories of the complex processes of cell division, cancer, and cancer treatment.

Study 2 sought to distinguish the added value of constructing versus critiquing qualitative graphs: two essential components of metarepresentational competence with respect to graphs (diSessa & Sherin, 2000). This study showed that critiquing and constructing graphs each revealed different strengths in students' abilities to integrate their knowledge of science and graphs, both during the unit (Research Question 1), and by the end of the unit (Research Question 1). Our analyses showed that the explanations of students who critiqued graphs differed in particular ways from those of students who constructed graphs (Research Question 1). Specifically, students who critiqued a given graph tended to more clearly convey narratives of the underlying process, and to acknowledge 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 mention science concepts in explaining the meaning of their graphs. However, students on both conditions gained similarly in their conceptual understanding following the unit, which suggests that constructing and critiquing graphs each benefit student learning in distinct ways.

Our interviews with teachers offered insights into the instructional context within which to interpret our findings (Research Question 3). Specifically, these interviews suggested that qualitative graphing may help certain students to understand science concepts through their graphical representations, but challenge certain other students whom one teacher described as being less inclined toward mathematics. They also pointed to teachers' roles in supporting students' learning from the graphing activities, and suggested that different topics and domain areas may present unique challenges for graphing.

Together, these findings suggest advantages for both critique and construction activities for promoting integrated understanding, particularly in the context of complex inquiry investigations. They both echo, and add nuance to existing research, which also found benefits in both critique and drawing for students' learning from visualizations (e.g., Clark, 2012; Zhang, 2010). One way to explain these findings is to consider the ways that each of construction and critique emphasize different aspects of KI, and at the same time, demand different degrees of effort. For instance, the pre-drawn graph given to students to critique was essentially an opportunity for *adding ideas*: It offered them new ideas that might have advanced their understanding or sparked an insight. Additionally, being relieved of the effort of having to construct their own ideas, *Critique* students may have been better able to focus on integrating science ideas to explain the graph. Meanwhile, construction required students to generate new material, which focused them on *eliciting* their existing ideas. However, this also introduced the possibility that students would not independently realize the pattern depicted in the graph given to *Critique* students (i.e., cycling treatment as a way to mitigate its side effects). Moreover, the time and effort spent on constructing graphs may have contributed to the finding that *Construct* students' written narratives of their graphs within the unit were less integrated than those of *Critique* students. At the same time, the exercise of organizing one's various ideas and of determining what graph to generate (i.e., *distinguishing ideas*) may have encouraged students to more effectively grapple with and sort out their various ideas about the conceptual meaning of their graphs. Ultimately, this activity may have prepared *Construct* students to later use graphs more fluently in solutions to new problems, as evidenced in their performance on the post-test.

Findings from this study resonate with related research, which shows that graphing and science knowledge may be mutually reinforcing: understanding the science content may help students interpret a related graph, and information from a graph may illustrate a scientific concept. For example, an ordering study of middle school students learning about photosynthesis, revealed that engaging with novel graph concepts prior to instruction about relationships between sunlight, stored glucose and plant growth, led to stronger understanding of the science than the reverse order (Wiese, Rafferty, & Linn, 2017).

The current study's findings on the value, as well as the challenges with constructing graphs, also resonate with prior research on learning by constructing representations. Some of this research suggests that construction encourages learners to integrate verbal with graphic representations, which results in the development of a mental model (Van Meter & Garner, 2005). For instance, Schwartz and Martin (2004) found that compared to students who were given solutions, those who invented their own representations as a way of understanding statistics problems, regardless of whether their representations were accurate, were better able to later apply strategies they learned in a traditional lecture to new problems. Other research found that children who drew diagrams rather than selecting from a set of given diagrams were more successful at solving logic problems (Grossen & Carnine, 1990). Similarly, Van Meter, Aleksic, Schwartz, and Garner (2006) reported that students asked to draw content before formally learning about it developed mental models of that content. While those mental models gave students an advantage in transfer and knowledge application tasks (de Jong et al., 1998; Kintsch, 1994), they did not necessarily provide the same advantage for recognition tasks (Mayer, 1993; McNamara, Miller, & Bransford, 1991). Similarly, students in this current study who constructed graphs performed better on the KI post-test, but not on the immediate task within the unit. Our study thus adds the example of qualitative graphing to other research findings on the value and shortcomings of constructing representations for conceptual learning.

The current study also contributes to research on students' difficulties with graphing. In spite of overall gains in their science and graphing abilities, we found that certain students continued to display misunderstandings of graphs that are consistent with those documented in prior literature (e.g., plotting individual points rather than trends, generating series of graphs to represent display single factors, plotting linear functions in spite of the actual trend; Mevarech & Kramarsky, 1997). Because they make such misunderstandings visible within an inquiry context, graph construction and critique activities can be opportunities for formative assessment, as teachers may use these to diagnose and guide students' thinking about the relationship between the graph and its conceptual meaning (cf. Hovardas, 2016). In further work, we might explore how misunderstandings apparent in students' graphing artifacts might relate to their conceptual understanding of the science. We might also extend beyond identifying students' misunderstandings to also identifying the resources that students bring from their other educational experiences to the task of graphing, and which might be productive starting points for developing more effective instruction (cf. Delgado & Lucero, 2015). To support these roles for graphing, future research might explore ways to better leverage the social and technological resources available in classrooms to support students' science and graph understanding. For instance, technology might help teachers to provide targeted, personalized guidance on students' graphing activities. Along these lines, we note several promising examples of the use of automated scoring on student-generated representations to generate appropriate guidance, including on students' graphs of velocity and density (Vitale, Lai & Linn, 2015), concept diagrams of energy, and drawings of chemical reactions (Gerard et al., 2016).

5.1 | Limitations and directions for future research

Replications and refinements of the study presented here will help to further its goals. For instance, as this study was done with two teachers from the same school, further research in other school contexts, and with a greater number of teachers, would strengthen the generalizability of our findings. In particular, teachers in this study were attentive to their students' progress and enhanced and extended the online materials through individual and whole class guidance. Their efforts no doubt supported the impact of our unit. Therefore, studying teachers who are not as familiar with the WISE system as those in our study might help to distinguish the role of the unit's design from that of the teacher. Additionally, examining teachers' approaches to guiding students' learning during qualitative graphing activities would inform ways to design environments to support and enhance their roles.

Future analyses might moreover investigate the role of various peer interactions in supporting students' learning from qualitative graphing activities. For example, how might sharing and discussing graph artifacts with peers impact the ways that students revise their own thinking? How might we use technology to promote productive collaborative learning with graphs, such as by enabling students to pool data and to share and comment upon one another's annotations of their representations?

Peer collaboration during graphing activities may offer further benefits for learning. As the curriculum activities reported here involved multiple kinds of collaborative interactions, future analyses might investigate their roles in learning. How, for instance, might sharing and discussing graph artifacts with their peers have impacted the ways that students revised their own thinking? How might future iterations of the unit use technology to promote productive and authentic collaborative learning with graphs, such as by enabling students to pool data and to share and comment upon one another's annotations of their representations?

Overall, this research shows promise for incorporating qualitative graphs into inquiry-based activities to strengthen students' understanding of both graphs and science. It also makes apparent the opportunities for graphs as tools for students to articulate more nuanced science understandings, and for researchers to know what and how students learn within complex, science inquiry contexts. This research can be extended by exploring qualitative graphing within topics beyond cell division and cancer treatment, with different kinds of problems, and different kinds of qualitative graphs (e.g., sinusoidal, parabola, cubic, square root, etc.). Findings from such efforts would inform the design of new instructional approaches and materials to support students' integrated understanding of science and graphs.

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