Preservice Elementary Teachers Using Graphing as a Tool for Learning, Teaching, and Assessing Science

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Abstract

Graphing is an important tool for seeing patterns, analyzing data, and building models of scientific phenomena. Teachers of elementary school children use graphs to display data but rarely as tools for analyzing or making sense of data (Coleman, McTigue, & Smolkin, 2011). We provide a set of lessons that guide preservice elementary school teachers to analyze their conceptions about graphing and use graphing to (a) see patterns in data, (b) discuss and analyze data, (c) model scientific phenomena, and (d) teach and assess inquiry-based science. Examples are adduced for how we guided and supported preservice elementary teachers in their conceptual understanding and deeper use of graphing.

Introduction

Graphing has been used as a tool for analyzing and interpreting the world around us for at least eleven centuries (Friendly, 2007). Graphing can render abstract concepts, such as the relationship between variables, more visually apparent and hence more concrete. Graphing played key roles in revolutionary scientific discoveries (i.e. Newton's laws, 1699; Boyle's law, 1662) and everyday engineering and scientific discoveries, such as where best to position armor plating on aircrafts (Wainer, 1992) and the source of a cholera epidemic (Wainer, 1992). While the skills and practice of graphing were included in the National Science Education Standards (NRC, 1996), they take a central role in the Next Generation Science Standards (NRC, 2013). Graphing is an important tool in each of the following NGSS science and engineering practices: 2. Developing and using models; 4. Analyzing and interpreting data; 5. Using mathematics and computational thinking; 6. Constructing explanations (for science) and designing solutions (for engineering); 7. Engaging in argument from evidence; and 8. Obtaining, evaluating, and communicating information.

When teachers have used graphs for instruction in elementary school, it has been mainly limited to observing graphical representations in books or interpreting basic graphical representations (Coleman, McTigue, & Smolkin, 2011). Teachers in elementary school have rarely incorporated graphing as a tool for visualizing, discussing, analyzing, or making sense of data or scientific phenomena (Coleman, et al., 2011). When students in elementary school have been asked to construct graphs, they rarely knew the reasons for doing so (Friel, Curcio, & Bright, 2001).

The reasons for the limited use of graphing in elementary school has not been well researched. However, Szjka, Mumba, and Wise (2011) reported that preservice elementary school teachers (PSTs) viewed graphing as more a function of mathematics than as an analytical tool useful for learning, teaching, or assessing inquiry-based science. There is potential for change, however. Roth, McGinn, and Bowen (1998) reported that PSTs who used graphing as a tool for understanding science activities in their preservice classes were later more likely to teach graphing as an analytical tool in their classrooms.

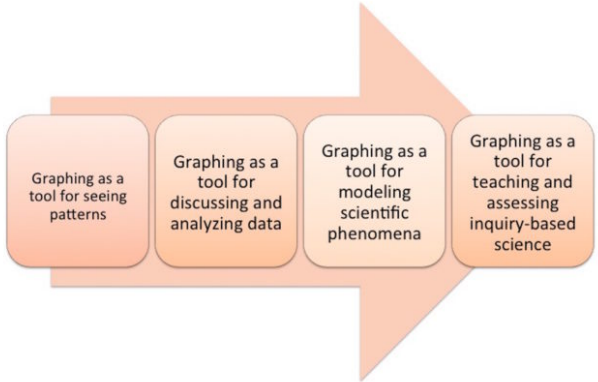
The Lessons

The set of experiences in this article was designed to help PSTs construct and use knowledge about graphing that could be applied in their teaching and assessment. In a 2017 study, teacher preparation courses that covered fewer topics with increased opportunity to unpack knowledge and apply that knowledge to teaching situations had a greater impact on the graduates' later teaching practices than teacher preparation courses that covered many topics (Morris & Hiebert, 2017). Thus, in this set of experiences, we provided opportunity for PSTs to reflect on, and analyze, their conceptions about graphing in a form that allowed them to apply it to learning and teaching situations. This was an innovative approach for us. Our prior teaching had not assisted PSTs in transferring their use of graphing as an analytical tool into their own instruction.

Overall, the purpose of the set of experiences described in this article was to guide PSTs to experience, discuss, and use graphing as a tool for 1) seeing patterns in data, 2) discussing and analyzing data, 3) modeling scientific phenomena, and 4) teaching and assessing inquiry-based science. In these experiences, inquiry-based science was taken to mean using multiple modes of teaching to guide students to discover or construct understandings about science instead of having teachers directly convey the information about science (Keys & Bryan, 2001). In this set of experiences, we strived to support the PSTs in moving along a continuum of using and applying graphing as an analytical tool in the context of inquiry-based science as shown in Figure 1.

Figure 1 (Click on image to enlarge)

Overview of Lessons



The context for our lessons was a one-semester elementary science methods course. This course was taken in the last semester of undergraduate study prior to student teaching. As a requirement of the course, PSTs planned and taught at least one inquiry-based science lesson in an elementary school classroom. As part of the course, PSTs also planned and delivered an inquiry-based microteaching lesson and an integrated STEM microteaching lesson to peers. PSTs were required to integrate math in one or more of these lessons.

Prior to the graphing lessons, we administered the 26 item multiple-choice Test of Graphing Skills (McKenzie & Padilla, 1986). The majority of PSTs demonstrated basic graphing skills (mean percent = 76.3, SD = 14.4; n = 77). These basic skills included selecting an appropriately scaled set of axes, selecting a set of coordinates, identifying manipulated and responding variables, selecting the best fit line, selecting a graph that correctly displays data, selecting the corresponding value for Y or X, identifying trends, interpolating and extrapolating from trends, selecting an appropriate description of a relationship shown on a graph, and identifying a generalization that interrelates the results of two graphs.

We built on this foundational knowledge with three focused lessons that guided the PSTs to use graphing in actual practice as a tool for 1) seeing patterns in data, 2) discussing and analyzing data, and 3) modeling scientific phenomena. These three initial lessons employed inquiry-based group work, direct instruction, and guided discussion to support PSTs to unpack their thinking and content knowledge about graphing as an analytical tool to build scientific understandings. The initial focused lessons occurred over three class sessions of one hour each during the second and third week of the course. Throughout the rest of the semester, we guided PSTs to extend and apply the knowledge from these lessons in their microteaching and field-based teaching and assessment. In this article, we show how PSTs' conceptions about graphing evolved to become more explicit so the conceptions could be used as tools for learning, teaching, and assessing science.

The sequence of three lessons began with a guided-inquiry experience that used graphing as a tool to make visible the relationship between the amount of space a volume of a solid occupies and the amount of space a volume of a liquid occupies (Author citation, 2014). The second lesson focused on using graphing as a tool to discuss and analyze data about the mathematical relationship between mass and volume of water and vegetable oil. The third lesson used graphing as a tool to model and compare the density of seven distinct homogeneous substances.

Lesson 1: Graphing as a Tool for Seeing Patterns

The first lesson guided PSTs to develop standard graphing conventions that enabled them to visualize the relationship between the volume of a solid and the volume of a liquid. In particular, PSTs used graphing as a tool to discover and see clearly the relationship between the volume of space occupied by a milliliter (mL) of liquid and the volume of space occupied by a cubic centimeter (cm^3) of solid. Our experience with this group of preservice elementary teachers indicated that a significant majority did not recognize this relationship prior to the lesson.

For the lesson, each group of three or four participants was provided a 0.5L bottle of water, 10 plastic 1 cubic centimeter blocks, a 100 mL graduated cylinder, and a metric ruler. They were asked to collect data and make a graph to show the relationship between the volume of the plastic cubes (cubic centimeters) and the volume of the water (milliliters) those cubes displaced. We used the following questions to facilitate discussion and support the PSTs to collectively design the investigation:

> What are the variables? What are their units of measurement?
>
> What could you do with the cubes to compare their volume to the volume of the water they displace?
>
> How will you organize your data as you collect it?
>
> Where does the manipulated variable go on the two column T chart? Is it X or Y?
>
> How will you design the investigation so you can measure the responding variable in step-by-step coordination with the manipulated variable?

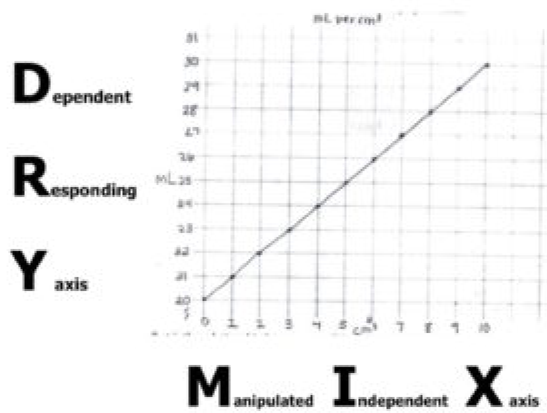
The questions and discussion led PSTs to suggest that they could drop the cubic centimeters one-at-a time into the graduated cylinder partly filled with water, record the measurements after each cube is submerged, and plot the data on a graph. We used plastic lab equipment and tap water that posed no significant safety concerns.

As PSTs investigated the relationship between the volume of a mL and the volume of a cm^3 using the method of water displacement, some of the PSTs initially confused the measurement of the amount of water in the graduated cylinder with the measurement of the total volume taken up in the cylinder which included both the water and the cubes. It was helpful to ask if the amount of water in the graduated cylinder had changed so participants could conceptualize the meaning of water displacement and develop the concept that volume represents the amount of space matter occupies.

As PSTs used graphing to display and see patterns in the data, it was important to bring attention to conventions in graphing that are commonly overlooked. These include the conventions of titling the scatter plot as Y vs. X, making a scale of equal increments on each axis, positioning the responding variable on the Y-axis and the manipulated variable on the X-axis, and drawing a best-fit line (McKenzie & Padilla, 1986). A graphic organizer with the mnemonic DRY MIX served as a teaching tool and a reminder for placing data on axes (Figure 2).

Figure 2 (Click on image to enlarge)

Teaching Mnemonic and a Student's Graph of mL vs. cm^3



The PSTs noticed and stated that graphing made the one-to-one positive relationship between the volume of a mL and the volume of a cm^3 clearly visible. They recorded their perceptions in writing and participated in oral discussion. During the discussion, we prompted PSTs to discuss aspects of the graphs that supported their understanding. It was helpful when we guided attention to the variety of ways that PSTs visualized and described the relationship as represented in Table 1. A word wall (Figure 3) also served as a valuable resource.

Figure 3 (Click on image to enlarge)

Word Wall That Added Oral and Written Explanations

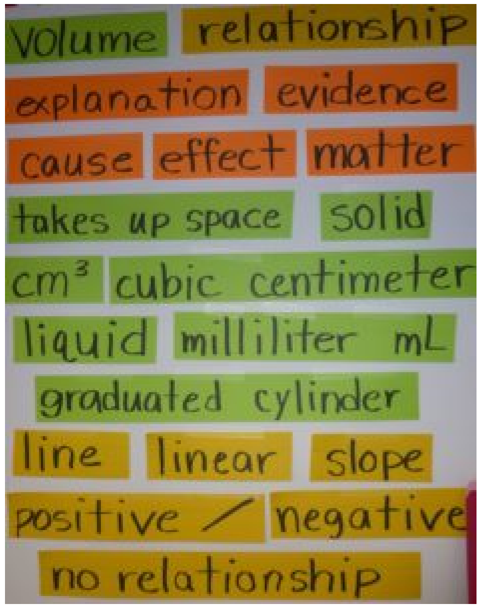


Table 1 (Click on image to enlarge)

Representative Student Responses During Lesson 1

What pattern did you see? In other words, describe the relationship between a millimeter and a cubic centimeter?
As the amount of cubic centimeters increases, the milliliters increase as well. This relationship is positive because they both increase so the line on the graph rises steadily up to the right. Because the cm^3 didn't change in unit size, the water level increased steadily and consistently.
They are directly proportional, meaning that they have a positive relationship. As one increases, the other increases at the same rate.
When there is an increase in cubic centimeters, there is also an increase in milliliters. There is a direct correlation between cubic centimeters and milliliters.
1 cm^3 = 1 mL. There is a positive relationship between a mL and a cm^3. The volume of mL increases by 1 each time you add 1 cube (1 cm^3). The graph shows a constant increase, which is shown by the graph of the linear line.
Whenever there is 1 cm^3 added, the displacement is 1 mL.
As the amount of cubic centimeters increases, they displace the water 1 mL per cm^3. The correlation is linear and seems to display that 1 mL = 1 cm^3.
This shows that water displacement can interchange cm^3 and mL as they are equivalent. Since both uses of measuring volume show that it takes up the same space, it is evidence that they can be changed to mean the same thing. They form a linear line where the slope is one.

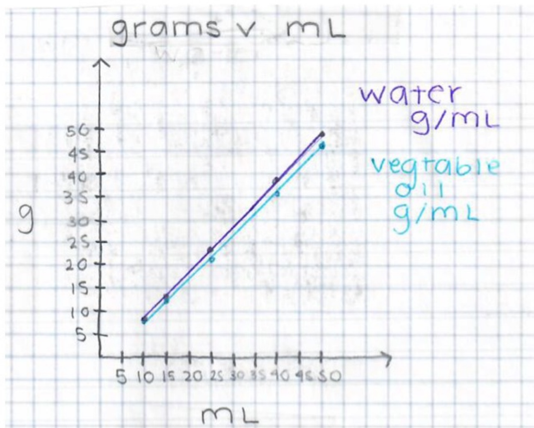
After the end of lesson 1, we prompted the PSTs to describe the role that graphing played in their exploration and understanding. One PST stated, "Graphing paints a picture. You can see things and use graphing to justify explanations." Another stated, "Graphs are visuals. They show how things look and how things work by making a picture of the data." One declared, "I liked that we got to see the concepts that we knew!" Another summarized the use of graphing as a tool, "Graphs communicate visually."

Lesson 2: Graphing as a Tool for Discussing and Analyzing Data

During the second lesson, PSTs used graphing as a tool to analyze data and discuss the relationship between mass and volume of two liquids: vegetable oil and water. Half of the PSTs in each class explored the relationship between the mass and volume of water. Half of the PSTs in each class explored the relationship between the mass and volume of oil. Prior to beginning the hands-on investigation, we demonstrated the procedure for using the electronic scales, discussed reading the liquid meniscus in the graduated cylinder, and reviewed standard graphing practices covered in the previous session. To challenge PSTs to properly scale a graph with equal increments, we directed students to collect data for 10 mL, 15 mL, 25 mL, 40 mL, and 50 mL of their liquid. To help PSTs with their discussions and analyses, we prompted them to calculate the slope of the line and discuss what the slope of the line represented (Figure 4).

Figure 4 (Click on image to enlarge)

PST's Graph of Mass Vs. Volume



For the final activity of lesson 2, students who explored and graphed the relationship between mass and volume of water partnered with students who explored and graphed the relationship between mass and volume of oil. We directed them to analyze data together by comparing graphs, describing relationships, and discussing possible reasons for the similarities and differences they observed. In other words, they were prompted to use the ratio of the relationship between mass and volume as depicted by the scatter graphs to discuss and explain similarities and differences between oil and water. The visual representation on the graph displayed the proportional relationship between the two quantities and helped lead the PSTs to attend to both quantities simultaneously.

As PSTs discussed the data and the relationships among the data, they were able to describe the meaning of the slope of the best-fit-line without using the word “density,” which helped them unpack their thinking and develop multiple ways to discuss, represent, and explain this concept. During the discussion, we modeled the use of a word wall as a resource in their discussions. After the students conducted the investigation, they noted that a word wall could serve as a tool to help their students bridge from everyday language to scientific language during discussions and data analyses. To help students unpack their conceptions about graphing, we brought attention to the diversity of ways that students analyzed and described the data (Table 2).

Table 2 (Click on image to enlarge)

Representative Student Responses During Lesson 2

What is the relationship between the mass and volume of water? The relationship between the mass of water and the volume of water is directly proportional. The slope tells us that for every 1 mL of water there is 1 gram of water.
What is the relationship between the mass and volume of oil? The relationship between the mass of vegetable oil in grams and the volume of vegetable oil in mL is positive. As the volume increases so does the mass. The slope is .944 g/mL. It is also a positive relationship. However, it is not directly proportional of 1 to 1 like water.
Compare the relationship between the mass and volume of water with the relationship between the mass and volume of oil. What are possible reasons for the similarities and differences? The relationship between the mass and volume of water and the mass and volume of oil are both positive. If you had one mL of each liquid, the mL of oil would have less mass. The relationships have different measurements because the water and oil are made of different kinds of molecules. The molecules of oil are lighter than the molecules of water.

After the end of lesson 2, we asked the PSTs to describe the role that graphing played in their data analyses and discussions. PSTs elaborated about the value of using graphing to visualize data. One stated, “Graphing makes it easier to see and read the data.” Another stated, “Graphing helps stimulate ideas and words. It helps you come up with ideas and explanations. It shows patterns so you can see and talk about them.” Another stated, “Graphing can help students explain when they don’t know because graphing can help you see and explain relationships.” Another PST stated, “Graphs can help you make a claim and justify the claim with evidence and reasoning that everyone can see.”

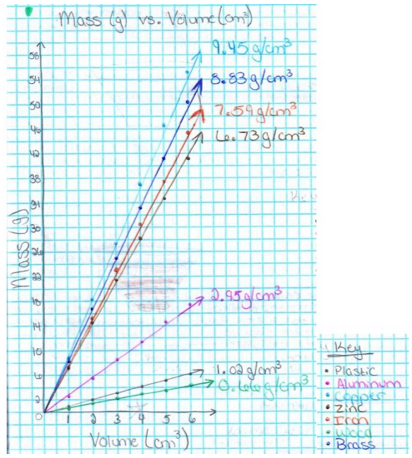
Lesson 3: Graphing as a Tool for Modeling Scientific Phenomena

Graphing is also a valuable tool in modeling approaches to science instruction as analyses and discussions of data are central to the approach (Jackson, Duckerick, & Hestenes, 2008; Lehrer & Schauble, 2004; NRC, 2012). This third lesson was similar to the second lesson, however, each group of PSTs selected different substances to explore. Sets of one-cubic centimeter cubes of wood, aluminum, copper iron, brass, lead, zinc, and plastic were available. PSTs were directed to use graphing as a tool to model the mathematical relationship between the mass and volume of the selected substances. The previous two lessons provided experience for participants to be able to design this investigation in small groups with little instructor guidance. We prompted PSTs to calculate the slope of the line, discuss what the slope of the line represented, and use this information in their models (Table 3).

To help PSTs synthesize a mathematical model of density, we prompted them to rotate around the room, share data with classmates, and add lines representing several different substances from the data they gathered from classmates (Figure 5). They compared graphs, compared relationships, and discussed reasons for the similarities and differences they observed. As they shared data, they were able to develop a model that represented the relationship between mass and volume that was valid across a variety of substances.

Figure 5 (Click on image to enlarge)

PST’s Graph of Mass Vs. Volume



In the final activity of lesson 3, we presented each group with a mystery substance (a 2 x .5 inch cylinder of brass, aluminum, or steel) and asked them to use their model to make and justify a claim about the identity of the mystery substance. In small groups, PSTs generated strategies about how to compare the mystery substance with the known substances. They measured and calculated the densities of the mystery substances and compared them to the densities of the known substances (Table 3).

Table 3 (Click on image to enlarge)

Representative PST Responses During Lesson 3

What is your substance? What is the relationship between the mass and volume of your substance? There is a positive relationship between mass and volume for zinc. As the volume increases by 1, the mass increases by 6.73g.
Use your model to compare the relationship between the mass and volume of the various substances. What are possible reasons for the similarities and differences? The relationship between the mass and volume for the various materials is proportional. Whenever the volume increases, the mass increases at a constant rate even with different materials. As the volume of aluminum increases the mass also increases. Therefore, the relationship is positive and directly proportional. There is also a positive linear relationship. Copper is the most dense of the substances because it has the highest mass per cm or slope on the graph. The least dense is wood because it has the lowest mass per cm. This is reflected in the slope of the lines on the graph. The relationship between mass and volume is called density. Copper is the most dense of the measured materials. While wood was the least dense. This can be seen in the graphs as the steepest and least steep lines. In each material, as the volume increased the mass also increased resulting in all them having a positive relationship. The relationship between mass and volume for the materials we used today varies, but maintains across all of them a positive directly proportional relationship. Copper has the greatest density of the materials and therefore had the greatest slope. The material with the least density was the wood with the shallow slope. Plastic was directly proportional with a 1cm : 1g ratio. The reason for these differences is that the substances are made of different molecules that have different masses.
Use your model to make and justify a claim about the identity of the mystery substance The mystery substance is probably aluminum. The best fit line of the volume and mass of the mystery substance pairs with the aluminum's line of best fit. This means that it is more probable that the ratio fits with aluminum. Most other substances have a greater mass per volume aside from plastic which it is clearly not.

After the end of lesson 3, we asked the PSTs to describe the role graphing and modeling played in their learning. One PST stated, “The graphic model helped us describe the abstract idea of density. It helped us use math to answer a question and it showed us how to use data and to represent data. It allowed us to work interdependently.” Another described the experience, “The graphs helped us talk about the strategies we came up with for the mystery substance. I found a lot of new ideas that way.” Another PST stated, “We were able to use data to make a model and to construct a reasonable explanation with the model. Graphing can communicate information. It (graphing) has many different purposes.” Another stated, “This shows that students can use math skills in reading, analyzing, and creating data and graphs for models. Modeling is useful to science because it helps make real world connections to actual events. It is important to make models for abstract concepts to demonstrate how the world works. I think that sharing was beneficial because it provides enough data to show a true trend." One PST summarized the experience, "This graphing and modeling connects math and science to the real world and real problem solving rather than just question answering."

Pedagogical Applications: Graphing as a Tool for Teaching and Assessing Inquiry-Based Science

Over the course of the three scaffolded lessons, PSTs took on more responsibility for planning the investigation, collecting the data, and using graphing as a tool for 1) seeing patterns in data, 2) discussing and analyzing data, and 3) modeling scientific phenomena. We helped facilitate this transition by prompting PSTs to do more, analyze their conceptions, and share their perspectives with each other. By gradually assuming greater ownership of the investigations, PSTs developed foundational knowledge, confidence, and initiative to use graphing as a tool for their own teaching over the rest of the semester.

Over the course of the semester, the PSTs analyzed, discussed, refined, and developed their use of graphing as a tool for learning, teaching, and assessing. Initially, some PSTs struggled to transfer their graphing knowledge and skills into actual practice, especially in ill-defined situations with unclear data. For example, a group of PSTs defaulted to using the collected data points instead of a scale of equal units when planning a lesson to guide elementary school students to graph and analyze the changes in stages of life cycle (larva, pupa, adult) of a population of mealworm beetles over time. In this example, the PSTs chose time as the variable for the X-axis. However, they initially used only the dates of data collection for values on the X-axis. The intervals between these values did not represent equal intervals of time. When the PSTs were prompted to identify the number of days between each value on the X-axis, they realized that some of the intervals represented 7 days while other intervals represented 10 days. They articulated that they had not used equal intervals. They also articulated that they could teach their students to create a scale of equal intervals by prompting the students to "skip counting" instead of just recording the dates of date collection. Therefore, it was important for the course instructors to continue to monitor and guide the PSTs as they applied their graphing skills in the development of lesson plans. Over time, the PSTs lesson plans began to show that they used graphing as a tool to engage their own students in seeing patterns, analyzing and discussing data, and modeling scientific phenomena (Table 4).

Table 4 (Click on image to enlarge)

Representative Excerpt From PST's Lesson Plan

NGSS Standard: 3-ESS2-1 Represent data in tables and graphical displays to describe typical weather conditions expected during a particular season. [Clarification Statement: Examples of data could include average temperature, precipitation, and wind direction.] [Assessment Boundary: Assessment of graphical display is limited to pictographs and bar graphs. Assessment does not include climate change.]

Chapter from textbook: Chapter 47

Driving Inquiry Question: How much rain does Phoenix receive on average each month of the year?

Objectives: 1. Students will be able to represent the average rainfall each month in Phoenix in a table. 2. Students will be able to create a bar graph to represent the average rainfall each month in Phoenix. 3. Students will be able to describe the rainfall in Phoenix over the course of a year.

Assessments:
Check in with each pair of students as they work on creating the data table for the monthly rainfall for Phoenix over the year. Check in with each student as they discuss the trends they notice. Criteria: Title of data table (1pt). Label of each part of data table (1pt). Data in table (1pt.) Participation in the peer discussion (2pt.) Peer reflection (1pt.)

Students will create a graph for the average rainfall each month in Phoenix and describe the rainfall over the course of the year. Criteria: Title of graph (1pt). Label of each axes (2pt). Equal scale of Y axis (2pt) Description of rainfall (8pt.), Trend notice (2pt.), Conventions of claim and evidence (4pts) Participation in the group discussion (2pt.) Peer reflection (1pt.)

Over the course of the semester, we asked PSTs to share their experiences and their perspectives about teaching science in elementary school. Unsolicited, the PSTs described graphing as a tool for both teaching and assessing:

> "For my evaluation I had the students pool their collected data and create a graph that explained what they had just completed with the number of coils and the strength of the magnet. I just love the fact that the students were the star scientists in this type of modeling."
>
> "In my class, we graph data and see how to apply math in our daily lives. Numbers are just numbers until we give them meaning. Graphing can give meaning to measurements and how it interacts with another variable such as time. I did a lesson about speed and time. I had the students make sense with real world applications and graphing. The students explored meanings rather than just taking science at face value. I think the making sense gives students a reason to want to learn more."
>
> "For assessment, a lot of that is done in their notebooks, I check for specific processes on certain days (charts, data, graphs, etc.) or I check for answers to certain questions. I can see what they know and answer any questions that students have. I comment on their thoughts and scientific knowledge that is brought out in the notebook. Using the notebooks and seeing the charts, data, and graphs really helps me gauge what concepts the students are grasping and which ones they are struggling with."

Conclusion

Children in elementary school need access to analytical tools, such as graphing, that help them make sense of the world around them (NRC, 2012). In this article, we provide science teacher educators with a set of lessons to prepare preservice elementary teachers to use and teach graphing as a tool to (a) see patterns in data, (b) discuss and analyze data, (c) model scientific phenomena, and (d) teach and assess inquiry-based science.

We built this set of activities on the belief that PSTs need a strong knowledge foundation about the use of graphing as a tool to be able to apply it to their teaching and assessing (Bowen & Roth, 2005; Morris & Hiebert, 2017; Roth et. al, 1998). Therefore, we provided PSTs opportunities to analyze their conceptions about graphing and to also discuss, refine, and improve their use of graphing in different contexts. To document progress and provide feedback, we reviewed PSTs’ written work samples and oral responses across the three lessons and across the field experiences and microteaching. We documented individual progress and provided feedback about the use of graphing to (a) see patterns in data, (b) discuss and analyze data, (c) model scientific phenomena, and (d) teach and assess inquiry-based science. Criteria for achieving these outcomes were incorporated into our course rubrics. Over time, we noticed that PSTs conceptions about graphing that were initially based on partial understandings, evolved and became more explicit. Compared to previous years, the use of graphing enabled these PSTs to be more descriptive, more precise, and more analytical when they made scientific observations, engaged in discussions, and problem solved.

While developing graphing abilities was a goal of the set of experiences, equally important was fostering the development of preservice teachers in viewing graphing, and its associated mathematical reasoning, as a tool for scientific inquiry rather than solely as something done in math. Compared to previous years, we noticed that these PSTs were more explicit in their lesson plans about how they used graphing as a tool to engage and assess student reasoning and scientific sense-making. The majority of PSTs showed in at least one of their three lesson plans that they were able to use graphing to support elementary school students in scientific sense-making and discovering or constructing understandings about science. These results are reflective of the novel and innovative approach we outlined in this article that guided PSTs to reflect and analyze their conceptions about graphing in a form that enabled them to apply those conceptions to new learning and teaching situations.

Finally, it is important to note that a limitation of this set of lessons is that each of the relationships that PSTs graphed represented a positive linear correlation. In future implementations, we think it is important to provide opportunities for PSTs to work with data that represent other types of relationships such as nonlinear, curved, exponential, etc. PSTs also need opportunities to work with, and explore, data for which no fully determined mathematical relationships emerge (this opportunity is available in Meyer, 2016). However, this set of lessons provided a starting point; linear relationships are a good place to start considering that linear relationships form the basis of many relationships in science.

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