From Graphs as Task to Graphs as Tool

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ABSTRACT

It is widely recognized that we need to prepare students to think with data. This study investigates student interactions with digital data graphs and seeks to identify what might prompt them to shift toward using their graphs as thinking tools in the authentic activity of doing science. Drawing from video screencast data of three small groups engaged in sensor-based and computer simulation-based experiments in high school physics classes, exploratory qualitative methods are used to identify the student interactions with their graphs and what appeared to prompt shifts in those interactions. Analysis of the groups, one from a 9th grade class and two from 11th/12th grade combined classes, revealed that unexpected data patterns and graphical anomalies sometimes, but not always, preceded deeper engagement with the graphs. When shifts toward deeper engagement did occur, transcripts revealed that the students perceived the graphical patterns to be misaligned with the actions they had taken to produce those data. Misalignments between the physical, digital, and conceptual worlds of the investigations played an important role in these episodes, appearing to motivate students to revise either their experimental procedures or their conceptions of the phenomena being explored. If real-time graphs can help foster a sense in students that there should be alignments between their data production and data representations, it is suggested that pedagogy leverage this as a way to support deeper student engagement with graphs.

Keywords: inquiry, laboratory science, critical thinking, discourse analysis

1 INTRODUCTION

There is an apparent international consensus on the need for students to gain proficiency in being able to visualize data graphically and interpret data graphs by age 14 or 15 (Binali et al., 2022; OECD, 2019; Pols, et al., 2021). The Next Generation Science Standards (NGSS) (National Research Council, 2013) are part of this consensus. Although it is natural to anticipate that the standards will have an impact on student experiences with graphs in the school science context, difficulties with graph interpretation continue to be documented at the middle school level and higher, both nationally and in countries that outscore the U.S. in international mathematics or science assessments (e.g., Binali et al., 2022; Boda et al., 2021; Matuk et al., 2019, Pols et al., 2021). Shah and Hoeffner (2002) found that most students recognized the communicative function of graphs but less commonly viewed them as a tool for thinking about data. Although it is widely agreed that we want to prepare students to think with and about data (e.g., Hardin et al., 2015; Hardy et al., 2019; Lovett & Shah, 2007), it has been surprisingly difficult to locate recent studies that investigate student uses of graphs of data they have collected.

The present study takes the stance that it is not only important to investigate student uses of data graphs in the context of thinking about their data, but that we need to know more about what can prompt students to do so. It draws a distinction between student efforts to *understand* graphical representations of data and their *uses* of graphs as a tool to support reasoning and further their knowledge production. If neither of these are occurring, students may simply be producing graphs as a product to hand in as evidence of completion of a school task (Bloome et al., 1989). Episodes from three small groups in high school science classes are used to explore a shift in each group somewhere along the continuum between creating graphs as a task and using them as a tool for epistemic purposes (examples of moving from "doing the lesson" toward "doing science," Jiménez-Aleixandre et al., 2000). Contrasting and comparing these cases can help deepen understanding of what prompted these shifts and what aspects of the instructional environment appeared to support them.

Two research questions guided analysis:

1. How were students interacting with their graphs? Were they only producing them or attempting to understand and/or use them?
2. If the students shifted in how they were interacting with their graphs, what appeared to prompt these shifts?

Although the focus of these science classroom implementations was on planning and carrying out investigations with simulations and classroom sensors and not on using graphs per se, the students used graphs to represent and analyze data they produced in the investigations. Transcribed sections of video screencasts of the three small groups were open coded and the resulting code list sorted according to whether the codes indicated evidence for understanding graphs, using graphs, or other. The open coding allowed for making distinctions within these categories, for instance when students shifted in how they were using their graphs. This formed a foundation for exploratory qualitative analysis of several episodes in which these three small groups were responding to on-screen graphical representations of data they had produced. Field notes will enrich the video record. Discussion will focus on how the results are congruent with and extend the literature on "doing the lesson" and "doing science" in the context of data graphs.

2 PRIOR RESEARCH ON STUDENT COMPREHENSION OF DATA GRAPHS

Much of the research on graph comprehension and use has focused on 7th and 8th grade students. Although the students in the present study were in high school, many of the issues reported for younger students appear evident in the screencasts the team collected. Perhaps this is not surprising; one relatively recent study demonstrated that college student performance on linear graph interpretation questions was similar to the performance of 8th graders on a national test in the U.S. (Bragdon, et al., 2019). Therefore, what follows is an overview of literature related to the interpretation of data graphs by learners middle school age and older.

2.1 Importance of attending to how students work with data

According to Lee and Wilkerson (2018), research shows that students benefit from working with data when such work is connected to meaningful inquiry, and when students have opportunities to participate in the construction, representation, analysis, and use of data as evidence in a coherent manner. However, Bernhard (2018) asks us not to neglect the role of experimental equipment because what students can discern is dependent on the technology they use. Also, Lee et al. (2021) caution that we are beginning to see undesirable societal consequences of too hasty an embrace of data and that there needs to be more attentiveness to the data processes students use.

2.2 Challenges with graph interpretation

Research in the 1980s on students from 7th and 8th grades and university undergraduates revealed challenges with graph interpretation. Most of these studies involved time series graphs and identified graph-as-picture conceptions, slope-height confusion, and difficulties interpreting the meaning of slope in science contexts (Clement, 1989; McDermott et al., 1987; Mokros & Tinker, 1987). More recent studies of graph construction and comprehension have continued to show the presence of graph-as-picture and slope-height confusion for many middle and high school students when working with graphs of motion or other time series data (Lai et al., 2016;

Vitale et al., 2015). There are some suggestions of improvement. A 2015 study indicated that middle school students were challenged by the interpretation of horizontal segments of line graphs (Vitale, et al., 2015), but reports from the 2019 National Assessment of Educational Progress (NAEP) (U.S. Department of Education, 2021) showed that most 8th grade students in the U.S. taking the science assessment that year were able to identify the horizontal segment of a line graph as the part that indicated no change. However, other challenges remain.

2.3 Challenges linking graphs with science ideas

Graphing is an important tool for thinking about scientific data (Lai et al., 2016; Shah & Hoeffner, 2002) but research from the 1990s to the present indicates that in general, children and adults find it challenging to link graphs with science ideas. Although variation in data is a key feature that both children and adults attend to, distinguishing whether that variation represents signal or noise seems to be a difficult task (Konold & Pollatsek, 2002; Masnick et al., 2007). Schauble (1996) demonstrated that people from middle school to adulthood tended to interpret the source of variation as error or true effect in line with their expectations. Kanari and Millar (2004) found that when there was variation but no clear trend, students struggled to interpret the results. When Croatian high school students were provided parallel problems in mathematics and physics, not only did students who understood slope in mathematics problems not understand the physical meaning of the same slope in the parallel physics problems, but they used different strategies to solve problems in the two domains (Planinic et al., 2012). When testing over 460 6th to 8th graders in the U.S. on graph interpretation, Lai et al. (2016) found that these students struggled to interpret graphs embedded in science contexts. They provided superficial answers and were unable to interpret the meaning of graphical features in the context of the system. More recent work shows that middle school students continue to find it challenging to comprehend data graphs and link them to the science concepts they represent (Boda, et al., 2021; Matuk et al., 2019). At least until recently, graphs have been underutilized in middle school science (Wiese et al., 2017). Measurement has frequently been taught in mathematics and not well-connected to measurement activities in science classrooms (Lee & Wilkerson, 2018). Recent results from the NAEP suggest that many students continue to arrive in high school not having met the middle school standards for graphing in the Next Generation Science Standards (National Research Council, 2013). For instance, on one released problem from the 2019 NAEP science exam, 43% of 8th graders were not able to identify which linear segment of a line graph represented the greatest positive change (U.S. Department of Education, 2021). On a released problem from the 2022 NAEP mathematics exam, fewer than a third of 8th graders were able to interpret a line of best fit overlaid onto a data plot with minimal noise (U.S. Department of Education, 2022). Studies in other countries that equal or outperform the U.S. on international assessments also report difficulties their students have with linking graphs to science ideas (Binali et al., 2022; Ivanjek et al., 2016) and in meeting international standards for data analysis and interpretation (Pols et al., 2021). Bragdon et al. (2019), in trying to explain why college scores on linear graph comprehension were similar to those of 8th graders on the NAEP, pointed out that if content is expected to be mastered before high school, it is unlikely it will be covered again in depth during high school or college.

When science teachers heed the standards to engage students with data graphs, the teachers may assume that what students have learned about graphing in mathematics will serve them better than it does. Literature on cognition, from both before and after publication of the NGSS standards, suggests several possible factors that make cross-disciplinary transfer difficult. Mathematics problems appear to require less processing of information and less conceptual understanding than parallel physics problems (Planinic et al., 2012). Understanding graphs in science requires knowing graphing conventions, decoding the visual features, identifying the graphical relationships being represented, and connecting these to the science content, usually in order to use the information as evidence or to predict something (Friel et al., 2001; Shah & Hoeffner, 2002). In other words, understanding such graphs requires both knowledge of graphs to recognize the pattern and knowledge of science to reason about possible causes (Lai et al., 2016). In an eye-tracking study, when subjects were shown graphs along with printed questions about them, both undergraduate and graduate students tended to look at the data almost immediately, whereas instructors appeared to look first at the surrounding information–axis variables, title, and legend (Harsh et al., 2019). Students especially have difficulty integrating features of graphs such as axis labels (Lai et al., 2016). However, integrating these features is necessary if one is to successfully link the graphs to the scientific relationships they represent.

2.4 Use of sensors and simulations with real-time graphs

By 2006, classroom sensors that could interface with computers and produce real-time data displays, or probeware, had become a common, though underutilized, resource in schools (Lee & Wilkerson, 2018). As of 2018, 85% of chemistry and 81% of all science classrooms in the U.S. had access to probes for collecting data (Smith, 2019). From the late 1980s through the first decade of the 2000s, a number of studies demonstrated the advantages for student learning. Use of probeware by undergraduate physics students was associated with dramatic improvements on velocity and acceleration questions, some of which included graphs (Thornton & Sokoloff, 1990), and successful tests with elementary and middle school students were also documented (Metcalf & Tinker, 2004; Zucker et al., 2008). Use of probeware increased the ability of 8th graders to identify the correct graphs for specific phenomena (Linn et al., 1987). A longitudinal study demonstrated that 7th and 8th graders' graphing misconceptions could be removed (Mokros & Tinker, 1987). Brasell (1987) showed that for high school physics students, a single class period with probeware resulted in improved comprehension of distance and velocity graphs as compared with a pencil and paper graph construction control group. Notably, a delay of only 20-30 seconds in displaying the data inhibited nearly all of the learning, suggesting the importance of near-simultaneous display of initial graphical information from motion sensors.

Other work has questioned these results, suggesting that kinesthetic feedback and control of a physical event may be more important than real-time graphs (Beichner, 1990). Leinhardt et al. (1990) pointed out that although the use of real-time graphs to describe data from experiments was a breakthrough in many respects, moving from pencil and paper graphing to computer graph construction has altered the nature of the challenge considerably. St. Clair et al. (2023) support those results. Lee et al. (2021) caution that automated data collection tools can undermine students' learning about important aspects of the data they are collecting.

Lee and Wilkerson (2018) note that many computer simulations intended for use in school science feature data in the form of graphs. These simulations may allow students to modify parameters and observe the effects of these modifications in the graphed results. Thus, a genre of these virtual labs can help students understand and treat the simulations as sources of data. However, they say, interpreting the data produced by simulations may not be straightforward for students for several reasons, including lack of student access to the algorithms that produce the data or the lack of variability or noise students might expect from real world data. Lee et al. (2014) point out that what data from simulations get represented in the graphs may depend on student data collection strategies (how to vary parameters), and student interpretation of results may depend on their data analysis strategies (such as inspecting a graph to obtain values for period of oscillation) as well as their ability to detect and treat outliers (such as might result from a subtraction mistake).

2.5 Student uses of time series data graphs

Shah and Hoeffner (2002) found that most students recognized the communicative function of graphs but less commonly viewed them as a tool for thinking about data. Although it is widely agreed that we want to prepare students to think with data (e.g., Hardin et al., 2015; Lovett & Shah, 2007), it has been surprisingly difficult to locate recent studies that investigate student uses of graphs as thinking tools, especially for thinking with their own data. In an older study, Wu and Krajcik (2006) investigated 7th graders' uses of data tables and graphs. These students, who had developed their own inscriptions from data, were then able to use those inscriptions to interpret their data. Although time series line graphs were not reported, they did use longitudinal bar graphs. Hmelo-Silver et al. (2015) reported that one of the teachers in their study supported middle school students to use an agent-based model with time series data graphs as a tool for thinking. As with these studies, the present study involves graphs of student-produced data. It adds to the literature by looking closely at how several students used their data graphs and what appeared to prompt and support those uses.

2.6 Summary

There is substantial evidence that in spite of an increased emphasis in science education on interpreting data graphs, many students still struggle. Although it is likely, given past research, that using real-time graphs in conjunction with simulations and classroom sensors can help, there does not appear to be much recent research on what it is in these activities that can prompt students to shift from a focus on producing graphs to using them as a tool.

3 DOING THE LESSON VERSUS DOING SCIENCE

During classroom observations, the author noticed times when students seemed to be focused on producing graphs as an assignment and other times when they appeared to be using graphs as a way to understand something about their world. "About their world" could be about the phenomenon of interest or about their physical or digital experimental equipment.

Various authors have described this contrast using slightly different terminology. Jiménez-Aleixandre et al. (2000) contrasted "doing the lesson" or "doing school" with "doing science." When "doing the lesson," teachers and students display a set of procedures to each other. Students use such procedural display (Bloome et al., 1989) to demonstrate to teachers that they have completed the academic task. However, familiar procedures can stand in for the accomplishment of something more valuable, as when students are required to complete a graph for each and every lab investigation regardless of the purpose of the inquiry (Windschitl, 2019).

Windschitl (2019) further probed the differences raised by Jiménez-Aleixandre et al. (2000), contrasting "doing school" with "disciplinary literacy." In his view, disciplinary literacy includes being able to use symbolic disciplinary tools as scientists do, such as when they produce graphs that play a role in generating or evaluating knowledge about the natural world. A similar notion was explored by Brown et al. (1989), who contended that to learn subjects and not just learn *about* them, students needed to be exposed to the use of a domain's conceptual tools in authentic activities rather than acquiring those tools and then allowing them to lie inert. Furthermore, one can acquire a tool but be unable to use it. "Similarly, it is common for students to acquire algorithms, routines, and decontextualized definitions that they cannot use and that, therefore, lie inert" (Brown et al., 1989, p. 33). According to Gravel and Wilkerson (2017), professional scientists and elementary students go through phases in adding new computational representations to their toolkits, from making sense of them to making use of them.

Related to the idea of "doing science" is Stroupe's (2014) idea of learning "science-as-practice." One of the four aspects of science-as-practice he observed in his study was when students embraced the "mangle of practice," a concept introduced by Pickering (1995). As Pickering described it, a scientist constructs a physical apparatus, which typically does not perform as expected. In response, the scientist seeks to bring his or her concepts and materials into alignment. This suggests one way to look at what is happening in moments when students become actively engaged in asking questions about their graphs, and that is in terms of alignments they may be trying to make.

3.1 Moving from "doing the lesson" to using graphs

In this study, *Using Graphs* refers to using the information in the graph in the authentic activity of helping further a classroom science investigation. It draws on Windschitl's (2019) ideas of disciplinary literacy (2019), Shah and Hoeffner's (2002) conclusion that graphical literacy includes being able to use graphs as a tool for critically evaluating data, and Lee et al.'s (2014) suggestion that graphs that represent data generated from either physical or simulated systems can be used to detect and treat errors introduced in data collection or analysis.

Understanding Graphs refers to the process of decoding information in a graph and mapping it to the real world. It draws on the early findings about graph interpretation as well as recent results from the NAEP (U.S. Department of Education, 2021) and other assessments (Lai et al., 2016; Vitale et al., 2015) related to identifying and interpreting graphical patterns and graphical features such as axis labels.

Doing the Lesson refers here to producing and turning in graphs without attempting to understand or use them, especially when utterances suggest that the students' intention was only to demonstrate that they could produce them without much regard for accuracy. This draws from Jiménez-Aleixandre et al. (2000) descriptions of activity that is meant to demonstrate completion of a school task, Bloome et al.'s (1989) notions of procedural display, and what Windschitl (2019) describes as "doing school."

That these concepts can be thought of as a continuum is supported by Gravel and Wilkerson's (2017) description of phases that professional scientists and students go through to get from *understanding* to *using* new computational representations. The continuum considered here arises from the data and is broader. It extends from turning graphs in without attempting to understand them, through concerted efforts to understand and interpret them, to what, in this study, is considered the most advanced interaction, using graphs to evaluate or generate knowledge about the natural world.

4 METHODS

During preliminary classroom trials of a physics unit developed by Concord Consortium's InquirySpace (IS) project, the author observed at least one small group produce a graph from sensor readings and immediately submit it to the teacher without reviewing it. This observation raised questions that led to the present study, which uses qualitative case study methods to examine video data from the following year of the project.

4.1 The InquirySpace (IS) environment

The IS browser-based, data exploration environment was designed for use in the classroom for data collection and analysis. This environment contains a *real-time graphical data display* embedded in the Common Online Data Analysis Platform (CODAP), an open-source visual data exploration tool (https://codap.concord.org). Readings can be fed into the digital environment from either digital sensors or simulations. The environment was designed to reduce the cognitive load associated with constructing graphs so that students can focus on designing their experimental set-ups and then on collecting, analyzing, and explaining their data.

In this environment the output from each student experiment can be represented in multiple ways: a real-time graphical display of sensor readings or simulation output, a data table, and data graphs that students can create using the data collected in the table (Figure 1). For instance, after running a series of experimental trials, a student could plot the dependent variable against an independent variable to see the relationship between the two. Such relationships are often expressed in textbooks as equations. The historical goal of “cookbook” style science lab experiments was to have students verify those equations, and the equation itself could be considered the explanation of the phenomenon under investigation. In that case, a graph could be viewed as a product for students to use to demonstrate attainment of the instructional goal. Although in CODAP a “fit line” feature can create a line of best fit and show the associated equation, neither equations nor graphs were the main goal of these inquiry-oriented learning activities. Instead, success relied heavily on students’ ability to analyze their data by constructing and interpreting graphs and data tables in order to make sense of phenomena.

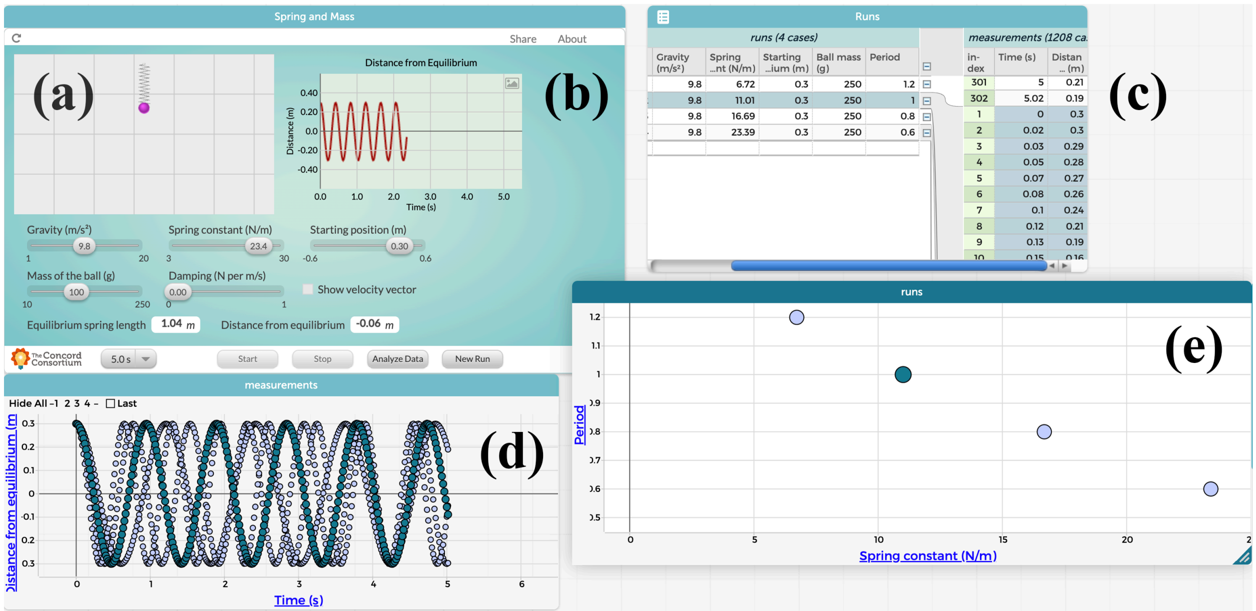

Figure 1 IS environment with (a) spring-mass simulation, (b) real-time display of readings from the current data collection run, (c) table of all data exported from prior runs plus variables derived from those data, (d) time series graph of the four runs from the data table, and (e) summary graph of the dependent versus independent variable, with one point per run.

Figure 1 shows the IS data exploration environment with simulation output. Students conducted experiments with the spring-mass simulation (a). The readings appeared in real-time graphs (b) and selected readings were exported to a data table (c). New variables can be defined in the data tables; for this experiment, the students defined a new variable *Period* and entered those values by hand. Graphs are made by dragging variable labels from the data table into a graphing area. In this case, (d) is a displacement over time graph with data from several runs displayed, while (e) is a summary graph of period vs. spring constant with one data point summarizing each run. The dark (teal) point in the summary graph has been clicked, which causes the corresponding row in the data table and corresponding run in the displacement graph to become highlighted. There is also an option to connect the data points to produce line graphs (shown in Figure 2).

4.2 Participants

The classroom implementations drawn on for this study were conducted in two suburban schools located in the northeastern part of the U.S. Students in the study were approximately 87% White, 5% Asian, 4% Black, and 4% Hispanic. Approximately 10% were eligible for free and reduced lunch. Schools were chosen for their proximity to the project development site and for the teachers' willingness to replace approximately three weeks of school instructional time with the IS physics unit. Teacher A taught four physics class sections (mixed 11th and 12th graders) that followed block scheduling, where each class met every other day for 80 minutes. Teacher B taught five class sections (three freshman physics classes and two senior honors physics classes) following a rotating schedule with most classes lasting 51 minutes and a long block once per week of 80 minutes. Seventy-eight students from Teacher A and seventy-nine from Teacher B consented. One or more project team members was present in the classroom for most classes, although not every class section was observed for every activity. Team members, including the author, helped troubleshoot software issues and sometimes intervened to instruct students on how to use the software, support them in data analysis procedures, or discuss physics content.

4.3 Physics unit

Students used a physics curricular unit developed by project researchers in consultation with the teachers that comprised a scaffolded sequence of increasingly open-ended explorations and experiments to gain experience in scientific inquiry. The activities were designed as suitable alternatives to lab-based standard treatments of physical science concepts such as linear acceleration and oscillation. The physics unit was bracketed by a pre/post-survey and included seven activities: a simulation to introduce the data exploration environment, three hands-on and simulated spring-mass activities to explore factors that affect period and amplitude, two parachute activities (simulated and hands-on) to explore motion with terminal velocity, and an independent experiment where the students used classroom materials in an experiment of their own design. After the teacher introduced each activity, students logged into the IS portal through their web browser. For each activity they were challenged to understand some phenomenon, guided by a series of portal pages that included information, questions, places for lab notes, and access to the data exploration environment. In each activity students generated and analyzed either simulation output or data imported from hands-on sensor-based experiments. Though the data were represented graphically, the focus was on learning all aspects of experimental design, from identifying an investigable question to designing an experimental set-up, analyzing data, and drawing conclusions. For Teacher A, each class section spent approximately eight periods on the unit over three weeks. For Teacher B, each class section spent about 13 periods over three weeks. Both teachers allowed approximately 10 hours total for time on task for the unit, though groups varied in how long they spent on their final projects. Teachers generally oriented each class to the plan for the day and then circulated through the room, interacting with student groups as needed. There were few full class discussions.

4.4 Data collection

All activities were conducted in the classrooms or adjacent hallways. The 157 consented students in these classes completed the pre- and post-surveys individually and worked in groups of two or three on the activities with one computer per group. All student work in the web-based environment was collected electronically and available to the teacher and researchers. The teachers were asked to choose focus groups of varying ability for more intensive observation.

Teacher A chose two small groups per class (eight consented groups). Teacher B chose three per class (15 groups, 13 of whom fully consented). Consented groups had additional screencast software running in the background of their computers; their voices and on-screen actions were automatically recorded throughout the class periods in the sequence. The author observed each class section between three and five times and took field notes.

4.5 Data selection: Three small groups

The team collected 219 period-long screencasts from 21 consented groups of either two or three students. Purposeful sampling was used at both the event and participant levels in order to choose a sample of qualitative data that could inform an understanding of the research questions (Creswell, 2013). Because the questions of interest concerned whether and how students used the graphs they were creating and what might have prompted changes in those uses, it was important to analyze activities that allowed the students the choice to use graphs (rather than focusing only on graph interpretation, for instance). Five activities met this criterion. They were the three spring-mass activities (hands-on and simulation), the parachute simulation activity, and the independent experiment. Review of the screencast videos focused on these.

From this corpus of data, the next task was purposeful sampling at the participant level. The goal was to dive deep into three representative groups demonstrating a diversity of engagement with graphs. First, classroom field notes were used to select candidate groups for further analysis as follows: the groups must have had complete sets of research screencasts, represented varying ability in physics according to their teachers as evidenced by their prior work in these physics classes and supported by the team's observations, and they must have articulated their thinking sufficiently to allow for analysis. In addition, the selection of groups should be as representative as possible of the entire data set. After reviewing the videos and field notes, three groups were selected that fit the above criteria. These groups represented both teachers, were from three different classes, ranged from freshmen to seniors, and had an even number of males and females. Group 1 was two 11th grade males and one 12th grade male from Teacher A, Group 2 was three 9th grade females from Teacher B, and Group 3 was one 12th grade female and one 12th grade male from Teacher B.

For these groups, the 5 focus activities occupied part or all of 24 screencasts (Table 1). For data-driven analysis, it is appropriate to select for analysis those portions of data that contain the types of activity to be described (Merriam & Tisdell, 2016). To address the research questions about how students were interacting with their graphs and changes in these interactions, the author, with the help of a second analyst, reviewed the 24 screencasts in Table 1 and flagged moments where data had been collected and were represented within the data analysis environment and where students were focused on these representations and referring to or writing about them. We also flagged any screencasts where students discussed the real-world meaning of patterns in their data even if graphs or data tables were not visible on screen, as this could suggest prior use of those data representations. Fifteen screencasts from these groups were identified as providing these types of information and subjected to in-depth analysis by the author.

For Group 1, all seven of the screencasts in Table 1 were analyzed in depth. For Group 2, the activities with simulations did not generate enough discussion for analysis. For instance, in their 46-minute screencast of the spring-mass simulation, Group 2 navigated through the software, read the instructions, planned their procedure, typed answers to questions about their procedure, tried out the controls in the simulation, spent four minutes generating graphs while engaged in occasional side talk, discussed what variable they might like to explore next, gauged how much time they had to finish the task, and performed two runs of the next simulated experiment without discussing the results. There was not enough on-topic discussion during the four minutes of graphing to reliably code whether they were unconcerned with accuracy or were dealing with time pressure by trying to be efficient and understand what they could in the time allowed. For this group, in-depth analysis was reserved for the five screencasts of their hands-on experiments, during which they discussed their graphs sufficiently to code their activity. For Group 3, who appeared comfortable with graphed data, only the first three screencasts were analyzed in depth. This group had rich discussions about the graphs in the spring-mass activities, but initial review of the remaining screencasts revealed that once they had explained these results to their satisfaction, they did not have much further discussion about their graphs. Rather, they worked methodically and competently through the remaining activities and through their independent experiment, which was a variation on one of the earlier spring-mass experiments.

The in-depth analysis, which focused on identifying how students interacted with their graphs and what might have prompted shifts in those interactions, was conducted as described below. In the interests of space, three episodes will be used to exemplify the results.

Table 1 Numbers in bold indicate the information-rich screencasts that were coded. Numbers in parentheses indicate screencasts that underwent preliminary analysis but were not coded (because focus of student discussion provided little evidence about their responses to graphs).

Screencasts analyzed in depth (Screencasts with preliminary analysis)				Spr-Mass Sensors 1	Spr-Mass Sensors 2	Spr-Mass Sim	Parach Sim	Indep Exper
Grp 1	Tch A	3 males	2 juniors 1 senior	**2**	**1**	**1**	**2**	**1**

Grp 2	Tch B	3 females	3 freshmen	**1**	**1**	(2)	(1)	**3**
Grp 3	Tch B	1 female 1 male	2 seniors	**1**	**1**	**1** (1)	(2)	(3)

4.6 Video analysis

The purpose of this study was exploratory and descriptive. Clement (2000) has described a continuum from exploratory studies that involve open interpretation of large, videotaped episodes by a single analyst to independent coder studies that can establish countable codes and frequencies of well-defined categories of observations. In between are studies that begin to separate theoretical concepts from observations so that observations can be compared across different subjects and episodes. This study fits the in-between case but is near the exploratory end of this spectrum. The author worked with a second analyst to develop a set of observation categories but did not attempt independent coding. The assignment of each code was established through consensus. Differences were debated and clarified through discussion.

When developing the codes ultimately used to describe episodes in the videotapes, the analysts utilized a construct development cycle (Glaser & Strauss, 1967; Miles & Huberman, 1994) leading to the progressive refinement of observation categories. First, the 15 screencasts were watched by one or both analysts. We flagged all episodes where students were either working with the graphs and tables or responding to unexpected data patterns. These episodes were assigned descriptive codes such as “use pattern in time series graph to determine goodness of data” or “interpret pattern in summary graph.” (See Figure 1 for an example of time series and summary graphs.) We also flagged episodes where students were evaluating their own thinking or their experimental process. Codes such as “reflect on quality of experimental procedure” or "reason about real-world causes of outcome" were assigned to these episodes. These observation categories were honed iteratively as we identified fresh episodes of student reasoning and examined them in light of previous episodes. Once the categories and descriptors stabilized, the author re-coded all relevant portions, then grouped the codes into larger categories of *understanding graphs*, *using graphs*, or *other*. This involved a process of inductive and deductive thinking that drew from Strauss and Corbin (1998). The categories were discussed with a third team member as a check on validity. (See Table S1 for a full list of these codes and transcript examples.) Because the codes and categories were exploratory, code counts are not reported here. Rather, the presence of codes grouped under understanding or using graphs was an indicator that the episode could yield information about those processes. Codes from multiple categories could be assigned to an episode. Next, working alone, the author examined and compared the episodes and created characterizations for each episode in terms of what the general focus of the group seemed to be, whether the students appeared to be using the graphs in authentic activity and if not, what they were doing with them. If no *understanding* or *using* codes were applied to an entire episode of student work with graphs, the author examined the episode further for indications that the students might have been *doing the lesson*, producing graphs to demonstrate that they could produce them without much concern for their meaning or accuracy.

The Results section is organized around exemplar episodes that illustrate how these groups were interacting with their graphs in the context of school science. The first two groups include episodes where they appeared to be closer to the "doing the lesson" end of the spectrum than to the "doing science" end. The Discussion section will consider how the findings relate to the literature on "doing the lesson" and "doing science" in the context of data graphs.

5 RESULTS

5.1 Group 1: From disengagement to reasoning about graphs

This group of two 11th grade males and one 12th grade male, in the class of Teacher A, varied widely on their focus depending on the day. They frequently joked and teased each other and did not always read instructions. However, toward the end of the unit, there appeared to be a shift in how one member of the group, especially, interacted with their graphs.

In the first exemplar episode, S3 was absent. S1, a junior, and S2, a senior, were responding to the appearance of a summary graph they had made for the second spring-mass experiment. (Figure 1e is an example of a summary graph.) Their three data collection runs to investigate period vs. amplitude were summarized by three data points. However, when typing in the values they had calculated for the period, S1 had inadvertently switched two of the values. When they connected the points to create a line graph, the result formed an inverted V. (The questions were in the online activity and the students frequently read them aloud.)

S2: Look at that!

S1: Yes.

S2: OK.

S1: That's one. (*One graph done*.)

S2: I guess. *(S2 sounds dubious, but they go on to the next page.)*

Q13. Did you make a graph of period vs amplitude?

S1: Yes. (*clicks the response*)

Q14. What is the shape of the graph?

S1: Line graph. Yes?

S2: Sure, sure. *(S2's voice sounds exaggerated, as though he is being facetious.)*

Q15. What does this tell you about the relationship?

S2: It's linear.

S1 (*laughing*): OK. (*S2 teases S1 and they joke back and forth*.)

Q16. Does the result match what you predicted?

S1: Sure, why not. (*laughs, types Yes*.)

S2: Yeaahhhh, OK. *(They go to the next page.)*

S2: You are a terrible experimenter. (*S1 laughs*.)

Q17. How do you explain the relationship you found between amplitude and period? Think about how the force of a spring and the velocity change as the amplitude increases.

S1: I don't even think we did this right.

S2: I'm pretty sure we didn't. *(S1 types: "The amplitude increases as the period increases." This is definitely not what their data show.)*

S2: Honestly, I just can't wait to be done today. (*They begin side talk*.)

Q18. Were you surprised by your results?

S1: Were you surpr- were, were-

S2: Yes! Yes we were! (*They laugh.*)

S1: Very! Duh. *(However, he clicks "No surprise.")*

S1 (*chuckling*): No surprise, we expected it.

(Having entered an answer for each question, they go to the next activity.)

CODES: Understanding graphs: none. Using graphs: none.

These students did not appear to be taking the activity seriously, not bothering to answer the questions in the activity truthfully even though they were aware they were being recorded and an observer was nearby. They did not use the graphs as a resource for answers to questions about those graphs, but intentionally gave answers at odds with their data. This and the other screencasts from the spring-mass activities were analyzed because they provided a rich understanding of this group's thinking. Very few “understanding graphs” or “using graphs” codes were assigned to them (and none to the episode above). Exceptions were when, for a few seconds each day, the students were looking at the real-time display (Figure 1b) as they decided whether to keep or discard sensor data.

A week later, while working on the parachute simulation (Figure 2), the author noticed a shift in S2's attitude. A second exemplar episode illustrates this shift. This time S2 and S3 were present. After changing the value of the parachute mass, S3 forgot to click the button to specify that he was conducting a new data collection run. This resulted in the previous value of mass being recorded in the data table for the new run (Figure 2d). In addition, the pair had inadvertently intermingled data from two different parachute experiments. In the first they had varied the mass, while in the second they had varied the parachute size. To add to the confusion, one of the runs in the parachute mass experiment had used size and mass identical to a run in the parachute size experiment. This meant that although they had conducted nine parachute drops (or runs), there were only eight data points visible in their summary graph of parachute size vs. final velocity; the data points for the two identical runs were on top of each other (Figure 2g). This seemingly chaotic experimental treatment in fact set the stage for some interesting student activity.

Shortly before the episode began, the students turned on the “show connecting lines” feature in CODAP and expressed surprise at the graphical shape that resulted (Figure 2g). Unlike the earlier episode, this time S2 became interested in figuring out the meaning of these data. Working together, the students clicked rows in the data table, which highlighted the corresponding data points in the summary graph, and clicked points in the graph, which highlighted the corresponding rows in the data table. As the pair worked to link these two representations of their data, they frequently moved their cursor back and forth between the data table and the summary graph, hovering over highlighted points. While they discussed the data table, S3 selected the rows corresponding to their second experiment. In the data graph, the points from their second experiment were now highlighted in red (Figure 2g).

S2: Wait a second! Hold on. Hold on. This straight line, that's the first half of the data. *(Indicates four data points in a horizontal line at the top of the summary graph, Figure 2g, all with the same value of parachute size.)*

S3: Yeah, but it doesn't mean anything because it's all different kinds –

S2: Right. So technically, the graph starts like that. *(Presumably gestures over the screen.)* Now I don't know why there's this big sp- Ohh. *(There is a spike in the graph.)* I know why. *(S3 scrolls through the data table.)* I know why it does that. Because we did that one last. So it goes in order of what we did. I don't think we can just rearrange it.

CODES: Understanding graphs: Interpret anomaly in graph, Identify pattern in summary graph. Using graphs: Use pattern in summary graph to determine goodness of data. Other: Reason about real-world causes of outcome.

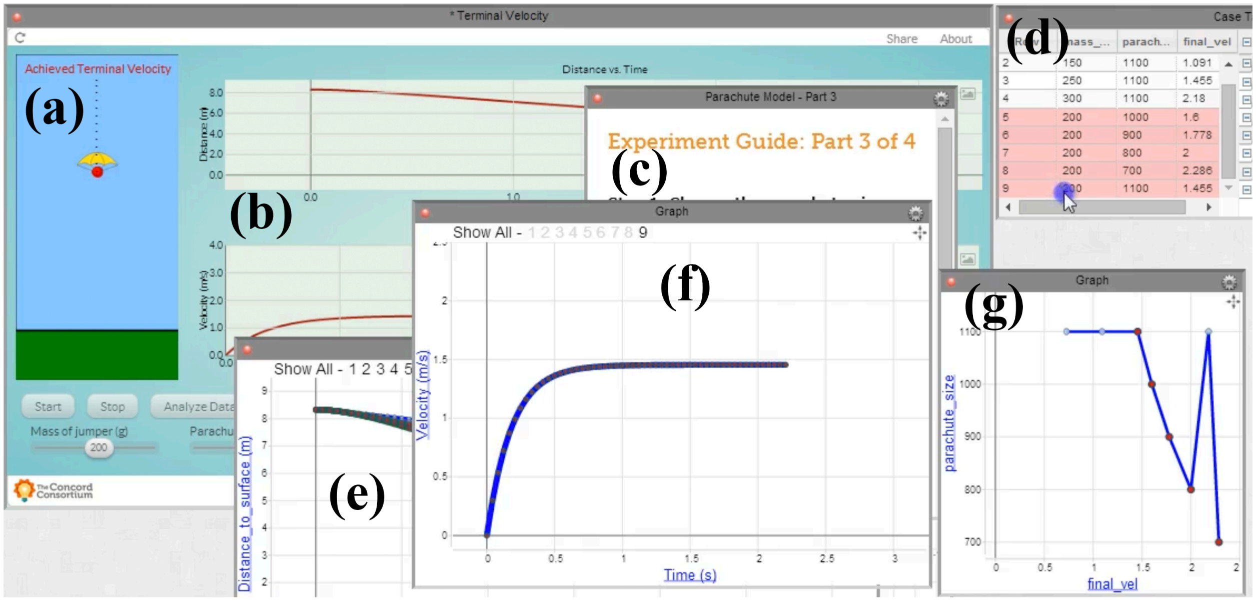

Figure 2 Screenshot from Group 2 screencast. (a) Parachute simulation, (b) two real-time graphs, (c) instructions, (d) data table with Rows 5-9 selected, (e) distance-time graph of multiple parachute drops (mostly hidden), (f) velocity-time graph with Run 9 showing, (g) summary graph with conflated data and an attempt to use the connecting lines feature.

S2's last statement, an attempt to align an anomaly in the digital world with something in the physical world, was incorrect; unlike the data table, the graph did not reflect the order in which the students conducted their runs. Rather, the data points from both experiments were mingled together in a single graph in order of increasing final velocity. The spike appeared because when the students selected "show connecting lines," the software connected the points from left to right. In spite of S2's lack of clarity about how the graph was constructed, which persisted until the following day, in this episode he was able to visualize how the first graph would have looked had it not been superposed; it would have been a horizontal line (the four points across the top). A moment after this episode, he also offered a description of how the second graph would look, "a diagonal line going down," an accurate, though imprecise, description of the second set of points, which form a descending curve. These students' attention was arrested by a summary graph that looked odd to them and they used additional data representations as they tried to figure out why.

The next day, with all three students present, they were faced with a similar situation. After receiving technical help to separate their data into two summary graphs, one for each experiment, one of the graphs again had an outlier. This time S1 clicked on the outlier and the group observed which row in the data table lit up. The three agreed that this row belonged to the other experiment. The students then carefully clicked on each point in each of their summary graphs to activate the visual connections between those points and the data table to ensure that their data were now divided correctly between the two graphs.

These students spent approximately 13 minutes over two days using their graphs to help them disentangle data from their two experiments with the parachute simulation. It appeared that something had triggered a shift away from their "doing the lesson" frame. Although the students who were present varied, S2 previously had not taken the activities seriously no matter who was present, and his shift in framing appeared most pronounced. The odd graphical shape certainly caught their attention, although an unexpected graphical shape during their spring-mass experiment had not triggered this kind of attention. In both instances, the students realized they had made a mistake. This second unexpected shape was odder than the first one and that may have piqued their interest. Or they may not have trusted their own data collection enough during the hands-on spring-mass experiments to be puzzled by an outlier. (S1 had said, "I don't even think we did this right.") It does seem clear that S2 was trying to associate the patterns in the graph with their own actions within the simulation, "I know why it does that. Because we did that one last." A lack of alignment between the curious shape in Figure 2g and the actions they had taken apparently prompted him to expend considerable energy to figure out in detail how the graphs were constructed. With this, he appeared to have shifted from "doing the lesson" (or "doing school") to being motivated to seek deeper understanding of the graphs and graphical features, including the meaning of the x-axis on a graph that was not in familiar time-series form.

5.2 Group 2: From completing the task to aligning digital and conceptual worlds

According to Teacher B, the three 9th grade females in Group 2 were good students. They exhibited some deep reasoning but also missed some on-screen details and were observed trying to search the internet with a smartphone for a correct "prediction" for one of their experiments. During the second hands-on spring-mass experiment, they gave evidence of approaching the activity in the spirit of "doing the lesson." After five runs to investigate the relationship between period and amplitude, they obtained the summary graph in Figure 3. They concluded there was no correlation between the two variables but did not attempt to reason why this might be. They did not notice how small the units on the y-axis were and did not appear to realize that if rescaled, the graph would have been, essentially, a horizontal line.

Q14. What is the shape of the graph?

(One of the students types, "It is random.")

S4: It is kind of like a quadrilateral. (*They laugh*.)

Q15. What does this tell you about the relationship?

S5 (*reading as S4 types*)*:* There is no correlation between period and amplitude.

Q16. Does the result match what you predicted?

S4 (*reading as she types)*: Not at all. *(They do not reason further about this but turn to making their video lab report. At the end of the report, S5 states their conclusion.)*

S5: So what we have concluded from this is that, is that period and amplitude have no correlation and each wave, no matter what the period is, can have a different amplitude.

(*The three students verbally sign off to end their video lab report.*)

S4: OK. we're good.

CODES: Understanding graphs: Identify pattern in graph; Interpret pattern in graph.

Although this episode was coded "Understanding graphs" because the students attempted to identify and interpret the pattern and to reason about a relationship between variables, they focused on the graphical shape and did not notice information about units on the axes (as is common, according to Harsh et al., 2019). Their words "no matter what the period is" indicate they saw it as varying. When there is variation but no clear trend, students can have trouble interpreting the results (Kanari & Millar, 2004). That was the case for these students: they decided correctly that there was no relationship, but for an incorrect reason. They did not try to figure out whether they could trust their data representation or what the real-world meaning of having random data points might be, but appeared to accept the graphs as representing "the answer." S4's comment, "We're good," suggests that understanding the graph and/or the phenomenon was not her primary focus at this time; they had an acceptable answer. During the next class period this group turned to the spring-mass simulation and had little focus on graphs.

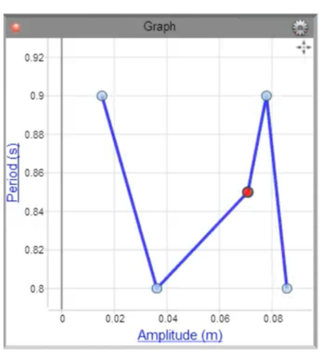

Figure 3 Graph created by Group 2. Students concluded, "Each wave, no matter what the period is, can have a different amplitude."

An episode during their independent experiment, at the end of the lesson sequence, provides a contrast. For their project, they had chosen to conduct experiments with a fan cart (a small cart propelled by a battery-operated fan), adding various masses to see the effect on acceleration. Rather than simply identifying a pattern and writing down a description, the students were now concerned about the appearance of their graphs, although whether this was simply from aesthetic concerns or because they did not trust their data was not clear. As the following episode began, these students had already spent 15 minutes over two days conferring with a project team member about their position-time graphs, modifying the orientation of their motion sensor, and changing their formula for speed so that they could get an upward rather than a downward curve on their real-time data display and speed-time graphs. The third day they were again getting negative positions, distances, and speeds, even with their new formulas (due to where they had defined the zero point; see Figure 4). The following excerpt provides clear evidence that the reason they were changing their physical set-up was so that the data representation would align with their conception of the motion (Figure 5).

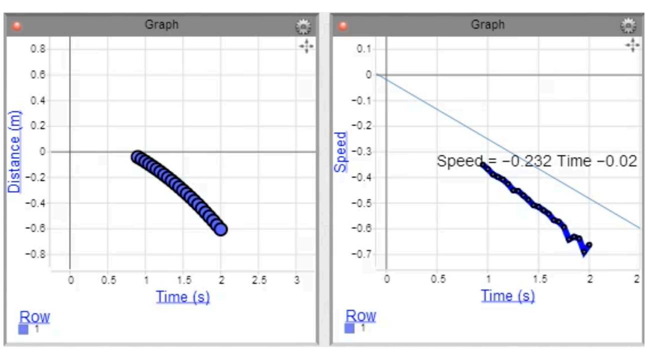

Figure 4 For the independent experiment of Group 2, due to how the students had positioned the motion sensor and where they had defined the zero point, the distances of their fan cart registered as increasingly negative. This resulted in negative calculated speeds and acceleration.

S4 & S5 *(overlapping)*: Why's it (the graph) still going down?

S6: Because it's going towards it. *(Fan cart is going toward the sensor.)*

S4: Oh seriously, supposed to go the other way?

S6: And this is you. So it's going towards you.

S5: One more time, guys.

S4: Are we going to go that way? *(With fan cart going away from the sensor.)*

S6: If you want it to go up?

S5: Yeah.

S4: Yeah. OK, let's go that way.

CODES: Understanding graphs: Identify pattern in position-time graph; Using graphs: Use graph as feedback on experimental procedure. Other: Reason about real-world causes of outcome.

S4 and S5 identified that the graph was "going down" and S6 reasoned about the real world cause for this. They decided to modify their experimental procedure as a result. S4's and S6's last comments indicate they now understood that the direction was not actually wrong; the students were making a choice to have their graph go up. This episode suggests these students were no longer trying to produce graphs just acceptable enough to hand in, but that they now had some greater investment in them. They had used the graphs as a tool before in a limited fashion to gauge whether each data collection run was sufficiently smooth or needed to be redone. Here, their runs were already smooth and S4's and S5's concern appeared to be with creating alignments between their digital and conceptual worlds, which required adjusting objects in their physical world as well. To this end, they invested in increasing their understanding of how their experimental set-up was resulting in negative patterns in their graphs. In the process, they were likely gaining understanding of what "positive" and "negative" meant in relation to linear motion. A plausible conclusion is that having graphs that reflected how they thought about their data had become important for their knowledge production during their independent experiment.

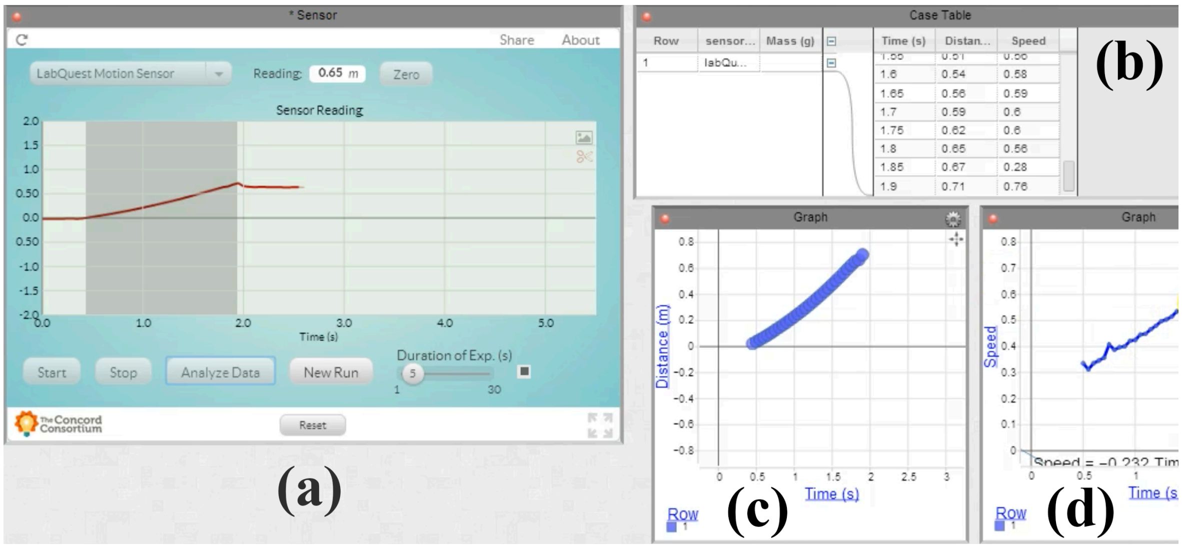

Figure 5 Distances, speeds, and acceleration of fan cart are positive due to repositioned motion sensor. (a) Students have selected a portion of data to export into (b) the CODAP data table for analysis. (c) Distance-time and (d) speed-time graphs reflect only the exported data.

5.3 Group 3: From using graphs as a source of information to using graphs as a foundation for reasoning

Group 3 had one 12th grade female and one 12th grade male in a class of Teacher B. They were already comfortable with graph interpretation. For instance, for one of the spring-mass physical experiments, they had observed that their summary graph looked like a step function, but immediately realized it was because the scale on the y-axis was so tiny that the graph would essentially be a straight line if the y-axis were more "zoomed out." (S8 joked, "If you squint so much that your eyes are closed, it would look better.”) In general, this group responded to graphical anomalies by identifying and interpreting their graphical meaning. To them, a graph did not just look “odd”; the shape meant something and they made sure that both members of the group agreed on the meaning before they moved on.

In addition to interpreting the graphs, they frequently used real-time graphs and occasionally their summary graphs to identify signal and noise and to decide on goodness-of-data for each of their data collection runs. They reasoned about causes for the phenomena they observed, though not necessarily when referring to their graphs. In the screencasts for their first two spring-mass investigations, a single brief episode for each investigation was coded as using a summary graph to reason about real-world causes. Thus they were already using graphs in most of the ways the project had hoped, as sources of information in the authentic activity of helping further their classroom science investigation. In the third spring-mass investigation, they began to use their graphs in another way, in order to help them puzzle out some knowledge about the real world that was new to them. This episode was not brief; it involved effortful sensemaking.

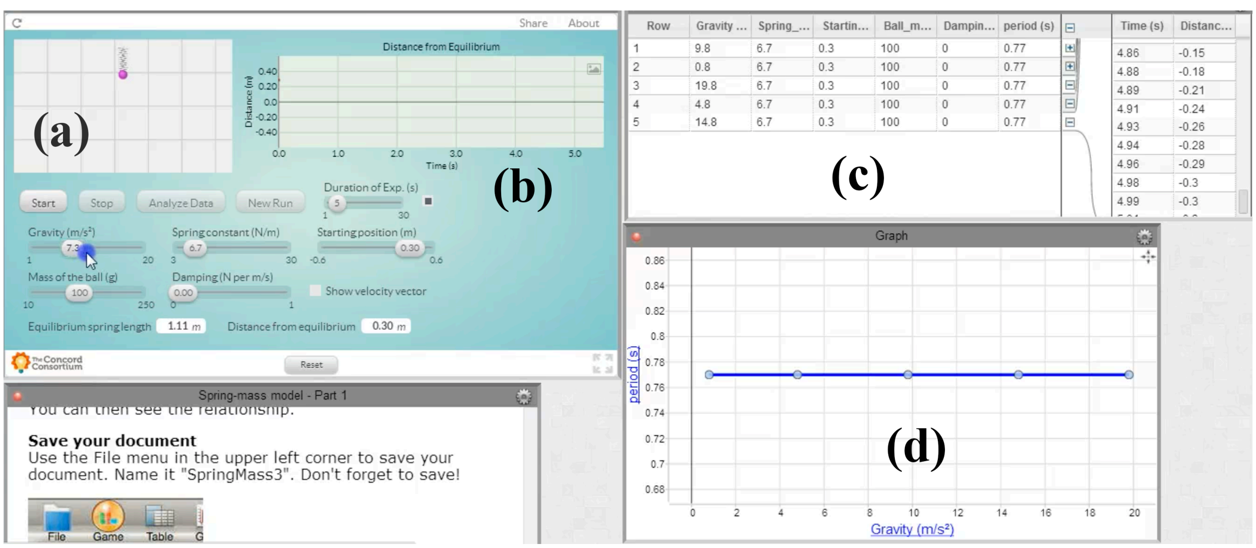

Figure 6 Spring-mass simulation with (a) the mass at rest, (b) real-time display cleared of data, (c) data table with five runs, and (d) summary graph with connecting lines showing no

relationship between acceleration of gravity and period. Student is manipulating the gravity slider in the simulation.

In the first two spring-mass investigations, S7 and S8 had conducted physical experiments with springs, masses, and motion sensors. Now, in the third investigation, they used the spring-mass simulation to investigate how the period might be influenced by gravitational accelerations other than that of Earth's surface (Figure 6). In the extended excerpt below, they were trying to answer the question in the online curriculum, “How would you explain this result?” They knew how to interpret the summary graph—they could see that the period did not change when they changed the acceleration of gravity—but this result did not make sense to them. As the episode began, S7 compared these results to the results of their earlier hands-on experiment in which the period *had* varied with different masses. Their hands-on experimental set-up, a mass hanging from a spring, was still nearby. (The transcript is annotated with descriptions of student actions from the author’s field notes. Ellipses indicate where the transcript has been lightly edited to reduce repetition and hesitations.)

S7: I don’t know, the other one *(experiment)* made sense to me, but this one does not. *(Handles physical mass hanging from spring, pulls it down.)* A spring on Jupiter. A spring on the moon. *(Inaudible.)* You’d think it would take longer to *(inaudible)*. *(pause)* I guess when gravity, when gravity is less powerful, then the tension in the spring is less powerful, cause it’s being – no, it’s being stretched out the same amount because the amplitude is the same. Why doesn’t the amplitude change?!

(They spend a minute and a half searching the web for an answer but give up.)

S7: If gravity is more powerful, it will pull it down – I just don’t understand! Because the tension in the spring (...) isn't affected by gravity. Right? *(S8 agrees.)* Yeah, so that means it should go further and take longer for the tension to pull it back up.

S8 *(softly)*: That didn't happen.

S7: My hypothesis is that the simulation is wrong! There is no way to explain this with science! Uhhh. *(They laugh and look back at the simulation.)*

S7: Here. What if we, let's vary, like, *two* things. So this is –

S8: No! Because –

S7: No no, I just want to see what happens. Because I need gravity to affect *something*! *(S7 moves the gravity slider slowly back and forth. The simulated mass moves up and down slightly. S8 notices that the reading for equilibrium spring length is changing as S7 moves the slider. At first they sound shocked, but then they decide that with less gravity acting on it, the mass will hang higher.)*

S7: Oh wait, so if it's higher up, when you start, like at low gravity – (…) and then you pull it down to here, there's going to be less tension in the spring than if it were regular gravity and you pull it down to here *(demonstrating with the nearby spring-mass set-up)*. There's more tension here – Ooh! OK. I got it. Alright. So, there's more tension, alright.

S8: Yeah. Explain it to me?

S7 *(using the spring-mass set-up to demonstrate)*: (...) So at low gravity, it's, the equilibrium length is like here, right? *(Holds mass up higher than its actual equilibrium point.)* So then the distance would be here *(lowers the mass to its actual equilibrium point)*. But from our gravity, *that's* the starting position *(indicating the actual equilibrium point).* (...) Whereas here *(holds mass up higher than its equilibrium point),* the gravity is weaker, but you have less tension when you pull it, so it can still have the same motion. *(pause)* OK?

Does that make –

S8: More or less. *(They start typing their answer, discussing how to word it in terms of the equilibrium spring length and the distance from equilibrium.)*

CODES: Understanding graphs: Interpret pattern in summary graph; Using graphs: Use summary graph to reason about real-world causes; Other: Reason about real-world causes of outcome.

These students responded to an unexpected graph as they always did, that the shape meant something and they needed to figure that out. However, this time they decided that it was an indication that something about their thinking was not making sense. They were already comfortable interpreting graphs—they had previously "acquired the tool" (Brown et al., 1989)—and they had quickly appropriated graphs to use as feedback about their experiments. Now they went beyond this to use a graph as a foundation to reason more broadly about physical concepts. They shifted their attention back and forth between the simulated and physical versions of the experiment in order to determine what, if anything, the graph of the simulation output was telling them about a real-world relationship. They did not accept the graphical data in an unthinking way, but worked to bring their conceptions and the feedback they were getting from their apparatus into alignment, as described by Pickering (1995). They concluded by recognizing a distinction between equilibrium length and amplitude in the case of a mass in harmonic oscillation. This distinction can prove difficult even for college students who have studied harmonic motion (Frank et al., 2008).

Although this kind of reasoning was not typical in these classes, there were similarities with the first two groups in what appeared to trigger deeper engagement with their graphs. As with Group 1, the shift for Group 3 appeared to be triggered by an unexpected graphical pattern that did not appear to align with the actions these students had taken in the simulation to generate those data. They had changed a parameter in the simulation using a slider bar but the graph showed no change. This pattern not only failed to align with their actions in the simulation, but it failed to align with their concepts about the physical world, as with the lack of alignment experienced by Group 2. As Group 3 attempted to align their digital, physical, and conceptual worlds, their attention moved back and forth between representations of those worlds: the onscreen simulation that produced the data, the on-screen graph, the physical spring-mass apparatus, and S7's hand gestures that conveyed his conceptions of what might be happening. Some of his gestures were made while he was looking at the monitor instead of at the apparatus he was using to gesture with, suggesting efforts to integrate digital imagery with mental imagery as he sought the new alignments. He appeared to be inviting his companion to integrate digital with mental imagery as well, to visualize data they had no way to produce physically.

For this group, it appeared that their interactions with the graph had shifted from being a tool in their data collection toolkit to being an epistemic tool used as both spur and referent in their own knowledge production.

6 DISCUSSION

The purpose of this study was to explore how students were interacting with their data graphs and, if shifts were observed in these interactions, what appeared to prompt those shifts. Screencast videos were analyzed and exemplar episodes from three small groups were used to illustrate the range of interactions observed in the classes.

6.1 Summary of results for RQ1: How were students interacting with their graphs? Were they only producing them or attempting to understand and/or use them?

Student interactions with graphs in the three exemplar groups ranged the full gamut, from turning graphs in without attempting to understand them to using graphs to generate new knowledge about the natural world. In two of the episodes, the students appeared to be focused more on producing than understanding their graphs. Group 2 had an episode that closely fit Bloome et al.'s (1989) description of "procedural display." They identified the pattern (or apparent lack of pattern) in their graphical results and interpreted it as meaning that there was no correlation between the variables, but did not dig further into why the results appeared random. Although they did not directly refer to having to do a task as in Jimenez-Aleixandre et al.'s (2000) examples of "doing the lesson," these students read the questions aloud, providing brief answers with occasional laughter and no explanations, then signed off, saying, "We're good." They certainly were not evaluating knowledge claims, offering justifications for different hypotheses, or engaging in other activity that would fit Jimenez-Aleixandre et al.'s descriptions of "doing science." However, considering the interactions with graphs observed in the study as a continuum, it can be noted that these students were not all the way at the far end of the continuum from "doing science." They tried, albeit briefly and superficially, to interpret the graph in terms of the phenomenon.

By contrast, Group 1 did not even attempt this in the first episode described for them. That episode exemplified much of the activity observed in their group. In it, the two students did not appear to be engaged in a good-faith attempt to display that they were getting the lesson done (Bloome et al., 1989) or to consume knowledge (Windschitl, 2019), so it seems a stretch to describe them as "doing school." When one of them replied untruthfully to a question in the materials by saying, "Sure, why not" and typing "Yes," the other laughed and responded "Yeaahhhh, OK. You are a terrible experimenter." If they were in the "doing school" frame, it was a frame of their own that did not appear to be shared by the rest of the class or the teacher, counter to the social construction of an event that Bloome et al. described as “doing a lesson.”

Somewhere toward the middle of the continuum might be episodes in which students exerted good-faith efforts to *understand* the patterns in their graphs. All three groups had such episodes. Group 1 struggled to figure out what an anomalous pattern meant and how it had been produced. This was an effort to understand the relationship between actions they had taken in the simulation and a pattern they saw in their graph that did not appear to align with those actions. One student struggled over two days to understand the meaning of a specific graphical feature, the x-axis in one of their graphs. Group 2 also tried to understand the relationship between their graphical representations and their actions, changing their actions to try to create the graphs they wanted. Group 3 successfully interpreted a pattern in their summary graph, but did not know at first whether to trust the result, “My hypothesis is that the simulation is wrong!”

Finally, all three groups *used* their graphs as well, although these uses varied. Group 1 used their summary graph to determine goodness-of-data, Group 2 used their time-series graphs as feedback on their experimental and analytical procedures, and Group 3 used theirs as a way to reason about real world causes and generate knowledge new to them about the effects of gravity in the natural world.

6.2 Summary of results for RQ2: If the students shifted in how they were interacting with their graphs, what appeared to prompt these shifts?

Each of these groups exhibited shifts somewhere along the continuum between turning graphs in without attempting to understand them and using graphs to generate new knowledge about the natural world. This shift was described for Groups 1 and 2 with two contrasting episodes. For reasons of parsimony, earlier episodes from Group 3 were only summarized and then contrasted with a single episode of extended reasoning.

Each shift was precipitated by unexpected graphical results, but unexpected graphical results did not always produce such shifts. In each case where they did, the students appeared strongly motivated to align their unexpected results with actions they had taken to produce the data. These actions all involved physical aspects, even in the simulations, where they dragged sliders to test different independent variables. Therefore, some of the new alignments were constructed between their physical and digital worlds. In addition, Groups 2 and 3 worked to create alignments between their conceptual and digital worlds. Group 2 worked to generate graphs that would align with their concepts about acceleration, while Group 3 eventually changed their concepts about the effects of gravity on a spring to align with their digital results.

Pickering (1995) describes professional scientists working to bring their physical and conceptual worlds into alignment, where the physical world includes their instrumentation. Here the instrumentation was partly digital, constituting a third area that needed aligning. The live display of experimental data as the data were being produced may have created a stronger expectation that the graphical patterns would align with the student actions, even in the summary graphs, where the association with student actions was not as close. If true, this is a complementary but different advantage of real-time graphs than reported in the early literature (e.g., Brasell, 1987), which focused on comprehension of distance and velocity graphs. The focus of Group 2, for instance, was not on comprehending the meaning of slope as much as it was on aligning the direction of slope with their conceptions.

The idea that graphs can be used as tools for the detection of unusual features in data is not new (Spence & Lewandowsky, 1990). However, consistent with Chinn & Brewer (1993), students sometimes ignored graphical anomalies, as Group 2 did in the episode where it appeared they were primarily interested in producing their graphs. When unexpected patterns were attended to, episodes for all three groups illustrate that the students could respond productively to them before they knew how to interpret those patterns, in several of the ways Chinn and Brewer described students responding to unexpected evidence. The point made here is that something had to motivate the students to attend to the unexpected and not simply accept the data as "almost literally self-evident" (Sandoval, 2005). For Groups 1 and 2, this required a shift.

Even when already operating in the "doing science" frame, students may go through phases in a journey from making sense of the graphs to making use of them (Gravel & Wilkerson, 2017), from using them to communicate to using them to think with data (Shah & Hoeffner, 2002). Group 3 attempted to do an internet search to find the answer to a question that asked them to explain their results. Group 2 was observed doing this on another day. However, the search did not help either group, and Group 3 moved on to using their graphs in tight coordination with their other tools to help them think about the phenomenon.

One other point can be made about these results. Stroupe (2014) argued for bringing Pickering's (1995) ideas into the classroom as part of learning "science-as-practice." He also argued that this requires students to become epistemic agents. If asking unprompted questions about their data and then taking time to explore them is taken as an exercise of epistemic agency, then all three of these groups exhibited such agency as they began to explore unexpected data patterns. S2 became focused on figuring out the meaning of the x-axis during the episode described and the other members of his group joined his focus the following day. S4 and S5 became very interested in figuring out how to make their graphs curve upward instead of downward. Neither of these issues were part of their assigned questions. S7 and S8 started from an explanation question in the materials but took their exploration farther than anticipated by the teacher. All of these students appeared to have moved beyond seeing data as "almost literally self-evident" (Sandoval, 2005), to having a strong sense that their data needed explaining and that the unexpected graphical patterns were important and worthy of sustained investigation. To that extent, they took responsibility for shaping their own knowledge production.

6.3 Limitations and implications

The goal of this study was not to test existing hypotheses or to establish a representative frequency of episodes, but to find instances of student reasoning and understand what prompted them (Clement, 2000). Although an attempt was made to choose representative groups, no claims can be made about the typicality of these episodes across the classes. Rather, the episodes illustrate what happened for these students in given contexts, and hence, what is possible; they are an existence demonstration, both of students using graphs as thinking tools while doing science and aspects of the environment that appeared to motivate and support this use. The author acknowledges that many other conceptual lenses could have been used to interpret these results. Furthermore, the final rounds of analysis and conceptualization of results were conducted by a single analyst, the author. However, validity was strengthened through the use of multiple observers, two coders, and discussions with knowledgeable members of the larger project team.

Although interest in whether students were using the graphs motivated the study, the focus on what produced shifts in these interactions arose during analysis. Future research could involve more rigorous investigations into what kinds of curricular or pedagogical supports could help support these shifts. A more challenging question is whether supports could be developed to a) help teachers recognize shifts in students' uses of graphs and other disciplinary tools when they occur and b) help make students' own shifts in practice visible to themselves. One possibility is to provide more scaffolds to teachers to help them seed whole class discussions.

The results suggest that introducing graphs as tools that students can use to aid their own investigations, with many of the mechanics of graph creation supported by software, offers the potential to be a powerful introduction to graphs, graphing, and the concept of variation in data, perhaps more so than the still common method of introducing graph construction and interpretation in the absence of physical data. A process of data production, exploration, visualization, and interpretation may be a more effective introduction than tackling these aspects piecemeal, especially if the process leads to students' perception of a need to create alignments between their conceptions of their own data and the graphical representations of those data. If true, this has implications for teaching approaches, lesson design, and the design of pedagogical materials.

7 CONCLUSION

The purpose of this study was to investigate student interactions with data graphs in the context of thinking about their own data, and to learn more about what can prompt students to use their graphs in the authentic activity of doing science. Considering these interactions on a continuum, from producing graphs just to hand them in to using the graphs as tools to help further science investigations, provided a way to detect shifts that occurred within larger categories such as "doing the lesson" or "doing science." Examining these shifts suggests that more than anomalous or surprising data were at work to motivate the shifts; the unexpected pattern present in each case appeared to the students to be misaligned with the actions they had taken to produce those data. This was true whether those actions had been taken in a simulation or with a physical set-up. If so, pedagogy with real time graphs might look beyond their usefulness to support graphical comprehension, and seek to leverage their potential to foster a sense in students that there should be alignments between data production and data representations, and to motivate them to produce such alignments, revising either their experimental procedures or their conceptions to do so. In this way, students would engage with graphs more deeply, more as scientists do.

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Table S1: Codes and Examples

NOTE: Codes were created deductively and inductively through iterative rounds of video analysis. These codes were sorted into categories according to whether they were descriptors of general classroom activity (e.g., students setting up equipment, consulting with a teacher) or described evidence of student engagement with the inquiry learning goals for the unit.

The author identified three categories related to student interaction with graphs in particular: Understanding graphs, Using graphs, and Other. Edited transcript examples are provided.

CODE	TRANSCRIPT EXAMPLE
Understanding graphs	
Identify anomaly in graph	S1: This doesn't look right though. (Indicating outlier with cursor)
Interpret anomaly in graph	S1: Like, mass of jumper and final velocity, why would it suddenly go down? That's weird. S3: Because you guys did an experiment where he had less mass.
Identify pattern in time series graph	S: Why is the graph still going down?
Interpret pattern in time series graph	S: Why does the graph show the velocity as negative?
Identify pattern in summary graph	S: (reading question in the materials) "What is the shape of the graph?" S: Just a line. S: A linear graph.
Interpret pattern in summary graph	S: (reading question in the materials) "Explain what this tells you about the relationship." S: It shows that it's proportional.
Identify patterns across multiple time series graphs or data table rows	(Looking at data table to figure out which points to include in a graph.) S2: You see (Rows) 1-4 right here? How they have all the same parachute size? S1: Different weights, though.
Interpret pattern across multiple time series graphs or data table rows	(Students have completed 3 data collection runs of the spring-mass simulation at different values for gravity. The time series graphs look the same for each run.) S2: Yeah, it might just be the same. S1: No, but it autoscales. S2: Ooh. That makes things interesting. Well, let's check it out. S1: Can we just do two more (runs) because it takes no time. (They do another run with a fourth value of gravity.) S2: I don't think it's changing the scale. I think it's just the same.
Using graphs	
Use pattern in time series graph to detect and/or treat noise	S: Oh, it's just weird. (Looking at motion sensor readings of oscillating mass hanging from a spring.) S: It starts going sideways by the end. (The mass had begun to move side to side in addition to up and down, introducing noise in the readings.)
Use pattern in summary graph to detect problems	S: I'm pretty sure something's wrong! (Laughing at unexpected arrangement of data points in their summary graph of 5 points.)
Use pattern in time series graph to determine goodness of data	(Referring to a dip at the end of their position vs. time graph.) S1: What's with that? S2: That's when he moved it. (S3 had moved the sensor before the run was done, apparently when he thought it was no longer collecting.) S1: Ah. S2: Yeah, you need to destroy that data.

Use pattern in summary graph to determine goodness of data	S1: I clicked on that (data point summarizing a run). That's not supposed to be in there. S2: So why is (data collection run) number 7 in there? (They look in menu for options.) S3: Delete selected cases? (This will discard the data from run 7.)
Use time series graph to reason about real-world causes	(In independent experiment, students are looking at the velocity-time graph of a real parachute drop. The velocity appears to have fluctuated but overall remained about the same, unlike their first drop, which had shown acceleration.) S1: That was an odd measurement. S3: OK, it's not too accurate but it does still show- S1: Well I mean, it actually could have gotten lower, like, the velocity, because as it was falling down, it was catching more air. S3: Whether it got lower or not, it doesn't matter. All it shows is that (the parachute motion) kind of leveled out.
Use summary graph to reason about real-world causes	(Their summary graph has all five data points in a horizontal row, indicating that the amplitude for all five simulated spring-mass runs was the same.) S: I don't know, the other (experiment) made sense to me, but this one- does not. S: A spring on Jupiter. A spring on the moon. You'd think it would take longer to do it. (pause) I guess when gravity- when gravity is less powerful, then the tension in the spring is less powerful, cause it's being- no, it's being stretched out the same amount because the amplitude is the same. Why doesn't the amplitude change?!!
Reflect on prediction in view of summary graph	S: I assumed it would affect the amplitude but not the period. And I was wrong about the amplitude. Because the amplitude was constant but I thought gravity would affect that.
Other	
Reflect on quality of experimental procedure	S1: So, yeah. So if it's like (pointing to differing masses in two rows of the data table) 300 and 200, then that's not like accurately measuring the parachute size effect.
Reason about real-world causes of outcome (without referring to the graphical representation)	S2: Oh wait, so if it's higher up, when you start, like at low gravity- wait, so if it's high up at low gravity, and then you pull it down to here (gesturing near the real spring-mass set-up), there's going to be less tension in the spring than if it were regular gravity and you pull it down to here. There's more tension here- Ooh! OK. I got it. Alright. So, there's more tension, alright. S1: Yeah. Explain it to me?
Use summary graph to answer question posed	S2: And our reasoning for that lack of relationship (in the summary graph) is because the higher the amplitude the more force acting on the thing, and that's why it moves more quickly? The higher the amplitude, the farther away from the rest point it will be so the higher tension you'll have, so the quicker it moves through- S1: The higher the velocity- S2: Yeah the higher the velocity- S1: So that's why the period doesn't change- S2 (overlapping): so it is constant.