Student Epistemic Agency and Coherence-seeking through Laboratory Experiments

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Abstract Overly simplistic school science laboratories constrain student agency. We share and discuss a case from 9th grade science classroom in which students all conducted highly varied independent investigations that were each highly coherent and scientifically well-motivated. We discuss the conditions that led to their experiments in terms of instability and uncertainty. Our findings suggest that it may be beneficial to support and recognize multiple forms of uncertainty simultaneously to encourage multiple forms of investigation to respond to those uncertainties. Finally, an "instability" caused by having *multiple* candidate models or explanations in play may be more generative than uncertainties based on gaps in knowledge.

Introduction

Recent efforts in K-12 science education have focused on the design of coherent curricular "storylines" (Sikorski & Hammer, 2017). Rather than "pre-meditated coherence" as a property of the curriculum, Sikorski and Hammer (2017) suggest that coherence should be seen as an emergent result of students' coherence-seeking. For this to be fruitful, students must be positioned with the epistemic agency to seek coherence for themselves— yet this still is rare within school science activities (Greeno, 2006; Miller, Manz, Russ, Stroupe & Berland, 2018). As a field, we are beginning to recognize that students must be positioned with epistemic agency throughout the full cycle of scientific inquiry—deciding on phenomena of importance, approaches to studying it, what forms of data are useful to collect, how to represent and analyze that data, and in argumentation from evidence.

However, when it comes to laboratory work in school science curricula, students are rarely positioned with epistemic agency. Epistemic agency involves students being "positioned with, perceiving, and acting on, opportunities to shape the knowledge building work in their classroom community" (Miller, Manz, Russ, Stroupe & Berland, 2017). In particular, experimental design, research questions, and methods of collecting and analyzing data are often strongly prescribed (Greeno, 2006; Hardy, Dixon & Hsi, 2020). Supporting student agency in inquiry requires educators to move beyond "cookbook" scientific investigations, to investigations that are motivated by student questions and ideas, and designed, carried out and iterated on by students. Doing "real science"— with the full complexity, uncertainty and messiness that it entails— is often in tension with narrow conceptual learning goals (Hardy, Dixon & Hsi, 2020). Moreover, school laboratory investigations rarely allow for or resemble the various forms of "coherence-seeking" found in professional scientific practice (Chinn & Malhoutra, 2002). Frequently, students all do the same experiment in parallel, or work to investigate the same underlying "driving question." Commonly, as part of teaching a "control of variables strategy," students may be asked to identify a parameter to vary regardless of whether "fair testing" or controlled experiments are actually motivated or appropriate.

Productive uncertainty

Building uncertainties into epistemic work may be a fruitful way to support both student epistemic agency and authentic scientific activity (Manz, 2018). Contending with uncertainty is an important component of science learning (Metz, 2004). Uncertainty has primarily been discussed as a sort of cognitive or metacognitive state of not knowing, for example in qualifying claims in the context of argumentation (Metz, 2004). In other views, uncertainty characterizes a state of ongoing activity that is recognized, maintained, or resolved by participants by re-organizing social or conceptual resources for that activity (Kirch, 2010). Uncertainty can thus play an important role in science learning by opening space for students to exercise agency. Uncertainties can be strategically designed into classroom activity such that students have opportunities to negotiate the forms of data to collect, how to represent data or phenomena, and what counts as evidence (Metz, 2004; Lehrer, 2009; Manz, 2015). Manz (2018) argues that this *productive uncertainty* should be evidenced by a variability, rather than convergence, of student ideas and questions and approaches. However, traditional laboratory investigations in science classrooms rarely promote a productive uncertainty, with the aims and results of these experiments often known in advance, and with a straightforward conceptual interpretation arrived at similarly by all students. The field needs a better understanding of how disciplinary uncertainties and ambiguities can be designed into students' laboratory work in ways that support student agency and deepened engagement in practice.

Instabilities in science practice

The view of *uncertainty* as a state of ongoing activity resonates with descriptions of science practice as an iterative, goal-directed "mangling" (Pickering, 2010) of conceptual, material and social resources. In Pickering's view, the material world resists the scientists' efforts to know and control; the scientist exercises agency in determining the future course of the activity by shifting goals, revising conceptual understandings, or modifying instruments and material practices. Over time, knowledge is established through processes of *stabilization* of these various elements of scientific activity. In authentic scientific investigations, there are many possible pathways forward; moments of 'material resistance' (Pickering, 2010) are characterized by uncertainty not only in how to interpret data but how to proceed in inquiry. Thus moments of material resistance are periods of *instability* in scientific activity, in which scientists exercise conceptual agency (Pickering, 2010). We conceptualize students' epistemic agency as an extension of Pickering's notion, to include the ways that students reorganize activity to align with their own interests, objectives, or desired learning trajectories. This includes shifting or forming new goals, or re-organizing conceptual (e.g., re-thinking, re-explaining, revising models) or social resources (e.g., taking on a new role, positioning someone else in a new role, drawing on available expertise in new ways). Our hypothesis is that uncertainty, as a form of instability in scientific activity, can provide opportunities for students to exercise conceptual agency, and align their empirical investigations with their own areas of interest or goals.

Research context and data collection

Our data come from a research project to design sensor-based labs that support computational thinking through data acquisition and control. Our designed activities were used in three 9th grade Integrated Science classes at a large urban public charter school in Northern California, taught by Mr. B. Over two weeks, students were introduced to the sensors and software, and conducted two investigations related to photosynthesis and cellular respiration. In the first investigation, students observed changes to carbon dioxide levels in container of spinach leaves when it was placed either in the dark or in the light. After a discussion of the results of that investigation, the students then conducted follow-up experiments of their own design. We observed all class sessions, video-recorded selected groups of fully consented students, collected written student work, and conducted follow-up interviews with 18 student participants about their experiences and their final investigations. One aim of our analysis, at this stage, was to better understand opportunities for student epistemic agency within the curriculum, and in particular how material resistances, or surprising "pushback" from the material world, may provide opportunities for student agency.

Case report: Student responses to instability and uncertainty due to an anomalous dataset

Part 1: Instability and uncertainty

After the initial introduction to the sensors and software, students were tasked with collecting data about the relationship between light intensity and CO2 levels in closed containers of spinach leaves. The teacher showed the students a demonstration setup that consisted of a plastic container, sealed with plastic wrap and placed inside a cardboard box that both held the lamp above the spinach leaves, and blocked out stray light. Over two class periods, each small group built a similar setup, and collected CO2 data under two conditions: with the spinach leaves under a bright lamp, or in the dark. With the light off, cellular respiration in the leaves will increase the CO2 levels in the container. When the light is turned on, the leaves then photosynthesize, and the carbon dioxide levels drop.

In each period, after groups had collected their data, Mr. B facilitated a discussion of the results. He began by establishing a class consensus about what trends they had seen in their data (carbon dioxide levels rising in the dark, and dropping in the light). Students readily offered the explanation that the levels dropped in the light condition due to photosynthesis. However, as we expected, they were surprised and perplexed by the rise in CO2 levels in the dark. Mr. B elicited the students' ideas about why they might rise in the dark. In each class section, some students attributed the rise to a reversal of the photosynthetic process of taking in CO2, and others to the idea that spinach was dying, and/or decomposing, when the light wasn't on to sustain the plant's health. In each class, Mr. B noted the surprising results, and their collective uncertainty about the explanation.

However, in Mr. B's Period 2 classroom, this discussion proceeded differently. Fernando's group had contributed a dataset that was very different than the others. Instead of constructing the cardboard box to hold the lamp vertically, they placed their lamp on the table nearby the container of spinach, such that when the light was on it was effectively at a much lower intensity. As a result, instead of the carbon dioxide levels going up in the dark and down in the light, Fernando's went up in the dark, and up (just more slowly) in the light. When he showed his data to Mr. B, Fernando initially thought he would have to re-start a botched experiment. However, Mr. B recognized the value of this anomalous dataset and brought it to the other students' attention.

In the next session, the class discussed their experimental results. Akeem suggested that the rise in CO2 was due to the plants decomposing when in the dark. Raeleen expressed skepticism about this explanation. Alejandra brought up Fernando's data, which showed the leaves releasing CO2 even when the light was on. This suggested to the class that rising CO2 levels may not be due to decomposition of the leaves. Fernando then took up the position within the discussion that plants are *always* releasing carbon dioxide, but photosynthesis may happen in parallel, just more or less slowly. Akeem wondered aloud how this would happen— whether the plants are doing something like breathing in and out. As in his other two class sections, Mr. B left the discussion in a state of uncertainty, and directed the students to design and carry out follow-up investigations.

Part 2: Student follow-up investigations

In Mr. B's two other sections, students chose many different variables to investigate: the intensity of the lamp, the color of the light, the type of plant, whether spinach leaves were kept in a sealed or open container, the age of the spinach leaves, or even to use leaves before and after being cut from a whole plant. Of these experiments, only this last one was conceptually motivated by their previous experimental results or the discussion of them. This group hypothesized that the rise in CO2 would no longer happen if they could keep the leaves from dying, by leaving them attached to the plant. In contrast, the students in Period 2 who had discussed Fernando's data each took on a variety of projects directly motivated by the previous experimental results and discussion. Below we briefly describe each group's follow-up experiment.

Fernando: Seeking additional data

Fernando requested an oxygen sensor to add his experiment. Oxygen sensors were not already available in the hardware kits, so we brought him a prototype. He wanted to re-do his first experiments, while additionally monitoring the oxygen levels as the carbon dioxide levels changed to see how they could be related.

Alejandra and Linda: Investigating an alternative hypothesis

Alejandra and Linda did not agree that Fernando's dataset was different because his light was effectively dimmer. Instead, they thought that his lamp did not heat the spinach as much as other students', and that the release of carbon dioxide could depend on temperature. They used their project as an opportunity to investigate this alternative hypothesis, through a unique experimental design to create extreme temperature conditions. They heated spinach in a water bath, and froze spinach in a freezer.

Akeem and Maala: Model development

Akeem initially thought that the plants were decomposing at night and releasing CO2, though this was challenged by Fernando's data, which showed carbon dioxide being released even in the light. Akeem was curious how the plants could both take in and release CO2, and thought that the plants might be doing something like breathing. He then reasoned that changing the amount of CO2 in the container might affect how quickly or slowly the plants breathe in or out CO2. Akeem and his partner Maala followed up by investigating the effect of starting CO2 levels on the plants' absorption or release of CO2, breathing into the containers to create the different starting concentrations.

Raeleen: Realizing implications

As Fernando's data showed that CO2 levels could either go up or down depending on light intensity, Raeleen recognized that this implied that they could find a balance point at which they remained steady. Her project became to create "flat data" by incrementally adjusting the light intensity. Her group added sheets of wax paper in between their lamp and spinach leaves to gradually dim the light.

Discussion

Each of the groups in Period 2 pursued investigations that were coherently linked to and motivated by Fernando's dataset and their own thinking about its explanation or implications. This contrasts with Mr. B's other two periods, in which students primarily conducted investigations that did not substantially build on the previous results or discussion. In Periods 1 and 3, there *was* a recognized gap in knowledge— no one was quite certain how to explain the rise in CO2 levels. This illustrates that simply *not knowing*— or, recognizing gaps in knowledge (here, their ability to explain the rise in CO2 levels)— is an insufficient condition for maintaining and motivating coherent inquiry "storylines." In particular, prescribing "fair testing" experiments, despite the apparent choices and design decisions involved, may fail to position students with epistemic agency by severing (potentially) continuous epistemic threads.

In contrast, in Period 2 there were many acknowledged sources of uncertainty, beyond the lack of explanation for the rise of CO2 levels: uncertainty about particular claims (whether the plants were indeed dying at night), mechanisms (whether plants do something like breathing), evidence (what did Fernando's data really mean?) as well as implications of their results (could the data ever be flat?). Further, the instability inherent in having *multiple* candidate models or explanations in play may have been more generative than uncertainty based in gaps in knowledge. This broader set of recognized uncertainties allowed for a variety of student independent projects to all remain conceptually tied to the classroom inquiry. Thus, we see uncertainties as opportunities for students to exercise epistemic agency, and to contribute uniquely to the scientific activity.

We agree with Sikorski and Hammer (2017) that coherence is an emergent property of student sense-making. To fully support student epistemic agency, even in laboratory investigations, we will need to allow for more variation in student empirical work. Our findings suggest that it may be beneficial to support and recognize multiple forms of uncertainty simultaneously, and to encourage multiple forms of investigation to respond to those uncertainties. Further, we will need to design ways to make students' varied individual contributions to epistemic work explicit— to ultimately weave together students' continuous epistemic threads, at the classroom level, into a collective tapestry.

Conclusions

To design for student epistemic agency in laboratory work we must consider and support forms of investigation beyond students all replicating the same experiment, or each investigating the effect of single variables. Instead, we can allow students to respond to various forms of uncertainties or instabilities with more varied forms and goals of empirical work (e.g. seeking additional evidence, investigating an alternative hypothesis, investigating a particular model, or realizing implications). This will involve creating and recognizing multiple forms of uncertainty and instabilities, and positioning students as capable of managing or responding to them.

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