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# Supporting learner agency with data to improve science classroom learning and culture

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**ABSTRACT**

The purpose of this qualitative study is to begin to identify heuristics for facilitating learner agency in Next Generation Science Standards-aligned science-as-practice-oriented classroom contexts. A framework for opening up science curricula to redistribute epistemic agency serves as a lens for analyzing generative facilitation of agentive science learners. Participants include one teacher and her students in four regular/non-AP freshmen and sophomore biology classes in an urban high school on the West Coast of the United States. Elements of curriculum that are designed in a way that increase learner agency include experimental design and choice of materials for answering questions about cellular respiration and photosynthesis, the data produced using novel Internet of Things (IoT) sensors, and claims from student experiments. We analyze classroom video and lab group screencasts from all four classes including two focus lab groups in each across the eight-hour long unit. Curricular adaptations such as providing minimal instructions and offering indirect discursive moves emerge as generative heuristics for facilitating learner agency.

**KEYWORDS:** scaffolding, epistemic agency, STEM, Next Generation Science Standards, professional development, science education, teacher education

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**The Problem**

Classroom laboratory experiments typically vary in their ability to support scientific inquiry. In most cases, students follow a set of designated procedures, use standard equipment, make observations, do analysis, and end with a write-up (Sentance, Barendsen, & Schulte, 2018). The value of these kinds of learning experiences focuses on time efficiency, scientific precision, reproducibility, and minimizing errors. Missing from these traditional, tightly orchestrated lab experiences are opportunities to empower students in formulating their own questions, designing measurement and experimental procedures, reflecting on possible sources of experimental error or data noise, considering the limits of measurements, possible inconsistencies in experimental setups, or erroneous assumptions underlying their design (Germann, 1996). In addition, the majority of science labs are too small, lack sufficient storage space, and are not set up in a way that promotes student engagement with science practices (Kauffman Foundation, 2007). In contrast, recommended phenomenon-based science-as-practice learning experiences incorporating the Next Generation Science Standards (NGSS Lead States, 2013) call on the field to orchestrate opportunities for learners to interact directly with or measure phenomena using the authentic tools, data collection techniques, models, and theories of science (National Research Council, 2012). However, opening class activities beyond observing, collecting, and analyzing data toward inviting student agency with the tools of science to *produce* data iteratively poses new challenges. Newly produced data must be examined for accuracy, sensor calibration, or noise to the point young scientists tinker or play with the materials enough to feel confident that the data they produce actually reflects what they intend to measure. Orchestrating such extended investigations today in science class is uncommon (Hardy, Dixon, & Hsi, 2019).

**Potential Significance**

One obvious reason such authentic experiences of science-as-practice in classrooms is so rare is the inherent challenge for teachers to open choices and decisions up to learners' trial, error, and discovery within tightly timed classroom schedules and high-stakes academic requirements. For this study, the question for research is: under these conditions*, how is learner agency best supported to foster authentic, sustained, and valued science practices?*

For the past three years, the Integrated Science Practices Enhanced by Computational Thinking (InSPECT) research team at the Concord Consortium has considered that question by adapting high school biology curriculum units to redistribute epistemic agency using unblackboxed Internet of Things (IoT) sensors as new tools for investigating environmental conditions ($CO_2$, temperature, light, etc.). Learners connect these to Wi-Fi enabled microcomputers to produce data and control devices that can be viewed and analyzed using Dataflow (Figure 1), a free visual program developed at the Concord Consortium (concord.org).

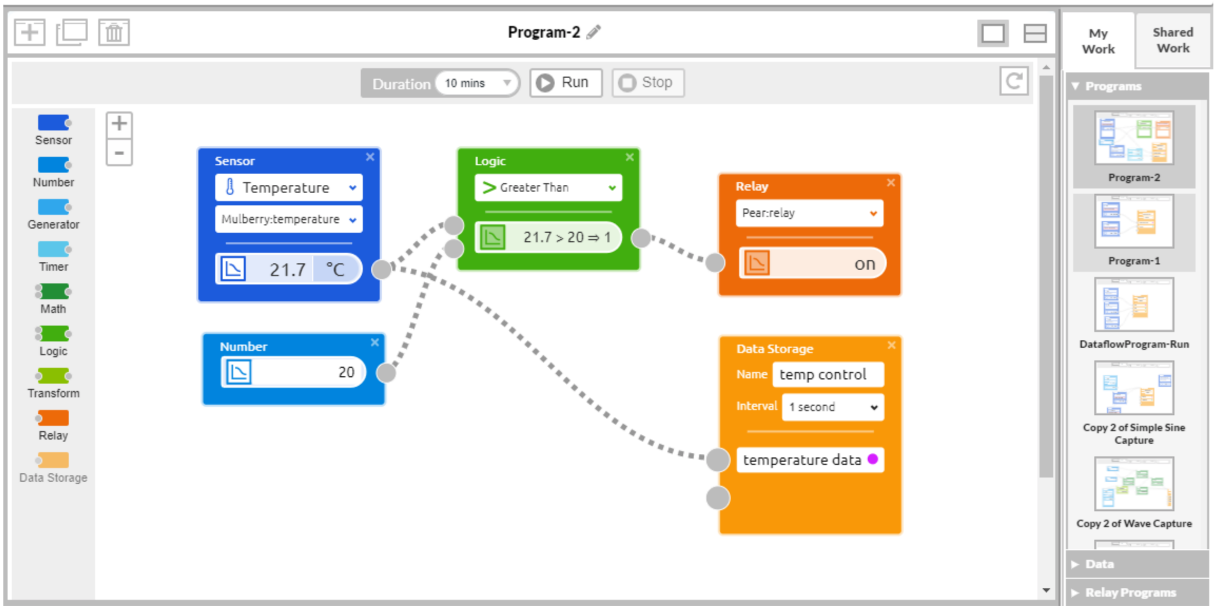


**Figure 1.** The Dataflow program records sensor data and actuates a fan, light, or other device with a relay. Logic and number blocks are used to construct if-then statements, which use conditional expressions (e.g., greater than) to control the relay. When the conditional expression is true, the relay is turned on. Data storage blocks preserve produced data, which can then be displayed using graphs.

Ko and Krist (2019) propose a framework for supporting teachers/facilitators of agentive learners, and include evidence of instructors effectively supporting learner agency. They delineate when and how to open up curricula in ways that shift classroom experiences toward science-as-practice, as recommended in the NGSS. Ko and Krist (2019) further suggest their framework might be used to surface "***how teachers gradually and incrementally make this shift, through practice, over time, and to develop heuristics for identifying and taking up opportunities to increase students' ownership and participation***" (p. 1003). There is little in the literature to date that provides a vision for educators, particularly at the secondary level, of how agentive activities might be realistically orchestrated and facilitated under the time-sensitive and high-stakes pressured environment of U.S. high school classrooms.

Our research, informed by classroom video and screencast data and triangulated by observation notes, student work, surveys, and teacher debriefs, begins to surface such a set of heuristics for whole-class teacher moves and small-group investigation facilitative moves that foster productive distributed epistemic agency to learner-doers of science.

**Theoretical Context**

Over the past thirty years, the focus of pedagogical reform in science education iteratively paves pathways away from "rote" learning activities and recipe-like lab experiences to demonstrated and structured inquiry activities, toward more authentic guided and self-directed inquiry learning experiences (Llewellyn, 2014). Early work includes Science for All Americans (1989) and Project 2061's Benchmarks for Science Literacy (1994) and the National Science Education Standards (1996), published by the National Research Council (NRC) of the National Academy of Sciences. Related curricular moves toward more guided inquiry-based activities involve real-time local data collection, sometimes using probeware, or analysis of actual field data drawn from publicly available databases to study patterns (e.g., in weather or populations), cause and effect, and other crosscutting concepts. Structured inquiry approaches scaffold appropriate processes while learners collect and analyze their own content to illuminate learning goals. The NGSS (NGSS Lead States, 2013) lays the groundwork for further steps by challenging educators to give over the responsibility for figuring out not just the "what" of science content, but also the "how" through guided and self-directed inquiry where students construct their procedure and analyze their findings (Llewellyn, 2014) in order to learn core scientific ideas. Science practices that are explicitly articulated in demonstrated and structured inquiry activities are now also handed over to students with the new standards (NGSS Lead States, 2013; NRC, 2011; Penuel & Reiser, 2017). This latest science-as-practice approach proposes a significant departure from previous reforms.

Before NGSS, the challenge for educators was to avoid lecturing or giving answers and instead to support student inquiry as experts in *process*, offering strategies and approaches for figuring out content. Today, the additional challenge is to support learners to ask their own questions about phenomena, to devise their own approaches to answering those questions and to make their own meaning of their evidence, while at the same time reaching pre-determined learning targets (Windschitl, Thompson, & Braaten, 2018). As epistemic agents or agentive learners, students now experience firsthand exposure to the "mangle" of practicing science (Pickering & Guzik, 2008) and "material resistance" found in the lab: variations in findings, loosely or poorly calibrated instruments, and trial-and-error iterative approaches to setting up and conducting experiments. Knowledge-building happens in the group collaboration or "dynamic interaction between individuals" (Stroupe, 2014). The role of the educator shifts to drawing out explanations for phenomena from learners. Knowledge is negotiated through social interaction.

Giving epistemic agency (Berland et al., 2016; Calabrese, Barton, & Tan, 2010; Schwartz, Passmore, & Reiser, 2017) over to learners for more agentive, science-as-practice learning significantly challenges educators as it requires leading by listening and following rather than planning exactly how classroom investigations will unfold (Hardy, Dixon, & Hsi, 2019; Miller, Manz, Russ, Stroupe, & Berland, 2018). Uncertainty must be sustained and supported. Efforts at providing what Miller et al. (2018) call "pseudo-agency," where class activities are still set up to go in some pre-anticipated direction, albeit less obviously than in rote-learning oriented classrooms, will likely defeat the authenticity of the experience for learners as they begin to notice they were not in charge, and were "tricked" into choosing a direction to go. On the other hand, a common misinterpretation that continues to challenge advocates of inquiry science, of simply sitting back and providing no support, is not the intention of the NGSS either. So what is the active role of teachers in this new context where uncertainty for teachers and for students is involved? What facilitative routines and discursive moves best support agentive learning? In this study, we examine where we observed space opened up for epistemic agency during InSPECT biology activities. We identify entry points implemented by teachers in support of agentive learners. An initial set of heuristics emerge from our work with classrooms of agentive learners.

**Design**
InSPECT integrates computational thinking (Grover & Pea, 2013, 2018) and NGSS practices by introducing novel IoT sensor kits into biology units on cellular respiration and photosynthesis. This innovative approach to engaging students in producing and analyzing data with sensors offers an example of the potential for learning science through firsthand experience, by employing computational tools to produce data and thus engage authentically in scientific inquiry about phenomena. Students produce data and analyze it using Dataflow, a software tool for writing programs and controlling sensor inputs and outputs. Dataflow utilizes visual programming to afford opportunities for learning and refining understanding of units and measurement, as well as controlling variables in authentic contexts. A basic program involves the collection of data from a single sensor. From there learners design more complex programs and investigations.

Using Dataflow, learners can study and sustain microenvironments and engage directly with the meaning of homeostasis, for example, not just the "what," but also the "how." InSPECT participants measure $CO_2$, $O_2$, air temperature, and light intensity data using sensors to then actuate a light, water pump, or fan for controlling the environment in a biosphere toward sustaining plant and/or animal life (Figure 2). They are encouraged to design and iterate upon their experimental setup, analysis of underlying biological phenomena, and even their investigable questions. They learn established high school biology content such as cellular respiration and photosynthesis as agentive learners: ***doers*** of science. In this way, computational thinking (CT) is leveraged beyond just observing and analyzing to actively producing data and thereby shifting to more *meaningful and authentic computational participation* (Hardy, Dixon, & Hsi, 2019; Lave & Wenger 1991).

A central question explored by this research aims to understand how this integrated CT and science approach impacts high school students' science ideas and their agency in science class: ***How can learner agency be supported to foster more authentic, sustained, and valued science practices?***

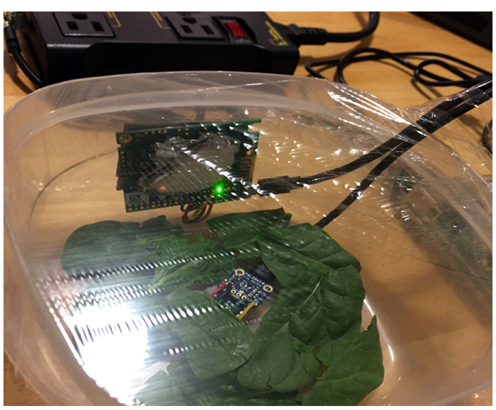

**Figure 2.** An experimental set-up for producing $CO_2$ and light data from a microenvironment. A $CO_2$ sensor is taped to the side wall of a closed container and a light sensor is attached to the plastic wrap.

**Methods**

For this qualitative study, researchers observed and recorded four teachers in six classrooms at three high schools during the fall term of 2018 and conducted a second observation cycle with one of those teachers in three of her classes in January 2020. Each class piloted an approximately eight-hour long biology unit on photosynthesis and cellular respiration. Initial survey responses about interest in science and technology, post-lab "reflections," student-produced artifacts, and online assessments were collected. Video of classrooms, screencasts of focus student groups, observation field notes, and semi-structured interviews with teachers were also recorded and transcribed by the research team (see Patton, 2003). All the students were informed about the study, and parent consent and student assent were obtained for all those included in the analysis. These data are still being examined to fully understand students' engagement and learning.

The present analysis focuses on teacher moves that orchestrate and maintain an agentive learning stance for student learners. By "agentive learning" we mean students are asked to move beyond just selecting from predetermined options: epistemic agency of *doers of science* rather than *receivers of science* complicates and localizes teaching and learning (Miller et al., 2018). What does the delicate dance of working within school-based constraints and shifting agency to learners look like? How is it fostered and supported by teachers?

One team member examined and iteratively coded the full set (27 hours) of fall 2018 classroom video and small lab group screencast data from four classrooms, all taught by the same experienced teacher (Erickson, 1986). Her initial selection is based on team analysis of where emergent heuristics for generative facilitative moves are most likely to be found, based on classroom observations. The researcher specifically sought patterns in instructional routines and classroom/lab discourse that indicated the maintenance of learners' agency. She created codes on the video notes and identified overall trends (Alozie, Moje, & Krajcik, 2010). Salient instructional routines and discourse that supported and sustained learner agency were then organized by related entry points delineated in the Ko and Krist (2019) framework for opening up curricula: methods of investigation, anchoring phenomena, and explanations constructed by students. The researcher consulted the literature, science education colleagues, and the classroom teacher as she reflected on analysis and triangulated data sources among classroom video, small-group screencasts, and student work with observation notes and teacher debrief transcriptions. She sought disconfirming or confirming evidence of the emergent heuristics (Merriam, 2009; Patton, 2003). Cases were selected for refining coding and descriptors of scaffolding that supported and maintained an agentive learning stance by students in whole-class discussions and in small group labs. Analytic memos surfaced an emergent set of productive curricular and discursive moves for opening up and keeping curriculum open to agentive learning. Instructional routines and discursive moves that supported and sustained agentive learning were identified and organized into a framework for opening up curricula in this way (Ko and Krist, 2019). Two cases, one from a small group lab and the other from whole-class discussion are presented. The work will continue as additional class and lab group video and screencasts are analyzed and reported in future publications.

**Limitations**

This initial research is bound by time and resource constraints. We have thus far examined the work of a single expert teacher teaching four sections of the same experimental curriculum. The authors represent an organization that supports ambitious science teaching (Windschitl, Thompson, & Braaten, 2018) and NGSS-aligned science-as-practice learning with technology. To address potential bias as researchers and curriculum designers of NGSS-aligned curricula, we invited the classroom teacher to review drafts and confirm the data and analysis (Merriam, 2009; Patton, 2003). The purpose of the study is not to claim generalizability, but to offer initial promising heuristics for iteratively changing and enhancing science teaching practice on the ground with the real constraints facing most teachers: externally mandated performance standards, large (20+) classes, limited resources, and tightly scheduled classes.

**Findings**

The study examines the following question: how can learner agency be supported to foster more authentic, sustained, and valued science practices? InSPECT activities include learning how to use the tools and then designing experiments to experience firsthand how exercise or use of energy results in higher energy burning or $CO_2$ concentration in our breath, or to sense and observe plant photosynthesis and cellular respiration as they occur under varying light conditions. Learners use evidence from their investigations to figure out phenomena, produce data, and regulate a biosphere.

An initial review of classroom video and observation data from the fall of 2018 and winter of 2020 reveals some useful heuristics for promoting learner agency that teachers can adopt. Two representative cases are presented in this paper. One case illuminates productive facilitative queries that support a small group lab team and the other demonstrates discursive moves during a whole-class discussion where the teacher guides a discussion comparing findings to the inherent disciplinary core idea (DCI) around cellular respiration without leading or telling. Small shifts in discursive support can make a difference in maintaining learners' epistemic agency.

Instructional routines are identified that neither tell students how to proceed (e.g., by troubleshooting or offering procedural advice) nor make them feel "tricked" by setting them up to come up with just the answer desired. Heuristics are organized using a framework tool for identifying junctures where teachers may open up or maintain openness of NGSS-aligned curricula designed for agentive learning (Figure 3).

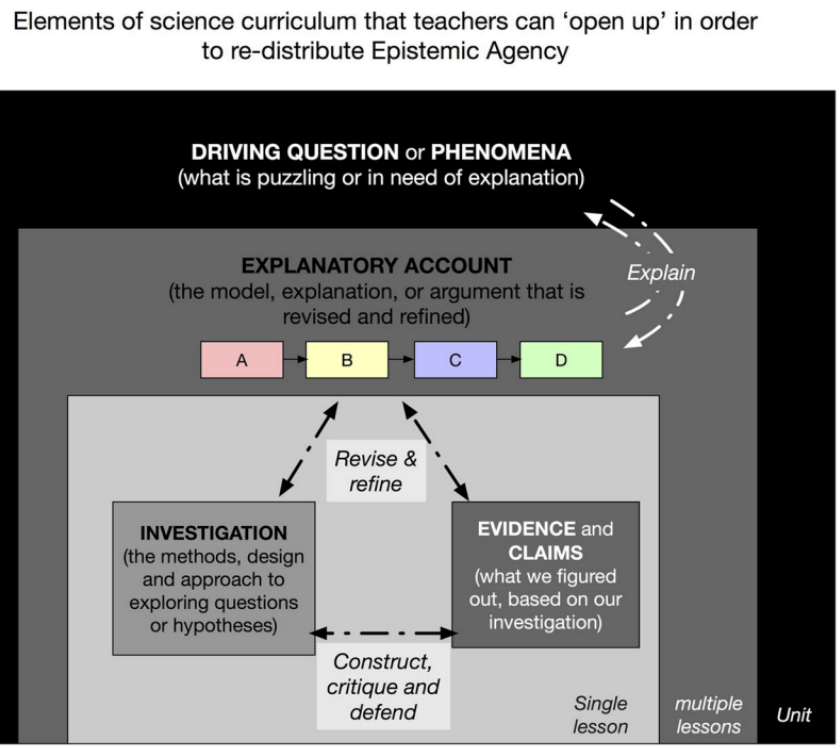


**FIGURE 1** Opening up science curricula to redistribute epistemic agency. The impact, or different levels of reach, of opening up these elements can be realized within a single lesson, across multiple lessons, or across an entire unit [Color figure can be viewed at wileyonlinelibrary.com]

Figure 3. Ko & Krist, 2019, p. 987. Reprinted with permission.

The emergent heuristics from InSPECT activities are organized in Table 1 below.

**Table 1.** Framework adapted from Ko and Krist (2019).
**Emergent heuristics for supporting and facilitating agentive learning**

| Ko and Krist (2019) framework: **Instructional Routines** | **Emergent Heuristics in InSPECT** |
|---|---|
| Sometimes anchoring phenomena determined by students | Can be biological, technical, or a hybrid<br>Students can ask questions they have the materials and tools to answer |
| Methods of investigation are uncertain | Students design investigations with new tools (un-blackboxed sensors, micro-computer, visual programming software)<br>Pro-tips handout available (procedures not dictated to whole class)<br>Demo set-up to reference or figure out (no whole-class walk-through)<br>Students encouraged to draw from peer set-ups<br>Materials available to select from (no specific procedures to follow) |

| | |
|---|---|
| | Indirect discursive moves for class discussions and coaching lab teams support learner agency and surface thinking |
| Ko and Krist (2019) framework: **Discursive Moves** (surfacing, not telling) | **Emergent Heuristics in InSPECT** |
| Generating evidence and claims from small group | Avoid direct troubleshooting. Instead ask...<br>● What are you trying to do?<br>● How are you planning to do that?<br>● Can you show me what you have so far?<br>● What do you think will happen?<br>● How would you deal with that?<br>● What evidence are you confident about?<br>● What data do you feel confident about?<br>● How confident do you feel about these data?<br>● What would make you feel more confident? |
| Generating alternative evidence and claims with whole class | Gather/focus on interesting differences rather than general “right answer” to surface/recognize/sort out sensor noise, data noise<br>Discuss outliers and variations<br>Suggest that students turn to their elbow buddy/group and discuss<br>Say...<br>● I’m hearing some of you share ideas<br>● What do we think?<br>● Who wants to add to that?<br>● Any guesses? |

The following two cases offer examples of these emergent heuristics. One draws from researcher interaction with a small group doing a cellular respiration lab. The other draws from whole-class discussion led by the teacher about the data produced and what the results show the class about cellular respiration and photosynthesis in plants.

**Case 1: Methods for investigation kept uncertain:** Small group lab work when researcher stops by to check in:

> A pair of students (one male, one female) have been stuck for a while on how to set up a light and dark test to compare $CO_2$ data produced under different conditions. One of the researchers visiting the classroom stops by. Student 1 makes a specific request: “We want to try to turn the light on and off when it gets too dark. We need help programming that.” Instead of “troubleshooting” by asking something like “Where is your light sensor?” the facilitator keeps epistemic agency on their side by asking questions about their plan and what they predict will happen as a result of their set-up and tests of varying conditions: “What does this program do right now?” “Okay, so what do you need to do?” Later, when the team is cleaning up, they are informally discussing the experience with the researcher. Student 1 states, “*I feel like I actually*

> *learned stuff today. I mean, I feel like we kind of exercised thinking by ourselves, working together to solve the problem. Usually in other classes we're not really...and even sometimes in this class we don't…exercise thinking muscles. I think that's kind of important. Most of it is regurgitating data and you kind of feel…like you have to, like on tests and stuff like [he makes a hand motion suggesting "put it back out there"]*.

**Case 2:** Generating alternative evidence and claims with whole class: Whole-class discussion led by classroom teacher toward Disciplinary Core Idea (DCI) for cellular respiration:

> A few days following a spinach lab experience, the teacher leads a class discussion with the goal of having students figure out that cellular respiration occurs constantly but photosynthesis occurs only with light conditions. The evidence is that their spinach never stops producing some $CO_2$ (from respiration), but the level of production trends downward with light conditions as the spinach photosynthesizes. She starts by asking groups to remind each other about their set-ups to bring the lab back to mind. She asks a few groups to share their data production trend lines. What do the data they produced look like? After some discussion of variance due to how the program takes data once per second (making the trends look like stair steps) and other reasons for messy data results (sensor noise, poorly closed containers), she turns to what they ***think*** the data tells the class about cellular respiration (not, **what** it tells them, but what they ***think***). When she **waits** and hears only silence, she suggests they turn to elbow buddies and share their thoughts with neighbors. Everyone starts sharing their thoughts. She moves among the desks and after a minute or so, she says, "I was talking to a few groups, can I have some groups share what they came up with…" By continuing to have students share quickly with elbow buddies sometimes writing down their thoughts, and then by validating their thinking by bringing the class back together with just a general acknowledgement like, "I heard some good ideas as I was walking around" to encourage sharing, she keeps progress moving forward until the class is able to figure out the DCI about plant cellular respiration and photosynthesis.

**Discussion**

In both of these cases, the more experienced guides play a key role supporting agentive learners to make progress within heavily scheduled classroom contexts where they do not have the same luxury of time that a scientist in a laboratory setting might have to figure out next steps. In the first case, when the researcher stops to assist the lab group, one student makes a specific request: "We want to turn the light on and off." Instead of troubleshooting by asking, for example, "Where is your light sensor in this program?," the response is to ask, "What does this program right here do?" and other similarly reflective and non-leading questions. Agency is maintained by the students. In the whole-class discussion, the teacher uses wait time and also supports advancing the discussion of cellular respiration and photosynthesis by lowering the stakes for publicly sharing thinking in a number of ways. She suggests students share their thoughts with neighbors first. She asks for guesses. And she circulates while students discuss their ideas with neighbors and then inspires confidence by saying something general like, "I am hearing some good ideas" to encourage whole-group discussion participation when she brings the class together. This instructional routine and others found in the data but not in these two cases are included above in Table 1.

Ambitious science teaching (Windschitl, Thompson, & Braaten, 2018) in today's U.S. classrooms is difficult. Science teaching no longer means telling students the history of science and lecturing about current scientific knowledge. It is not even serving as an expert on the process for students to tap as they investigate content. Today NGSS points to how science class should instead orchestrate students ***doing*** science. Shifts in teaching and curriculum authoring will be iterative. Ambitious instruction scaffolds learning by "providing opportunities for all students to learn science-as-practice by acting as epistemic agents" (Stroupe, 2014, p. 488). It deeply disrupts traditional understandings of what it is to teach as passing on knowledge to a new generation.

Preliminary analysis indicates that the potential for increasing student agency and motivation with IoT sensors and visual programming software is great. This paper offers examples of opportunities for agentive learning through firsthand experiences producing one's own data in classroom lab activities. In particular, given that a pedagogy of agency in science is in such early stages, our findings can help to clarify how teachers might recognize emergent lines of productive thinking or early entry points toward discovery of disciplinary core ideas (NGSS Lead States, 2013), as well as how best to foster peer-to-peer data discussions that support learners as they struggle with sensor and data limitations and more open-ended investigations requiring problem-solving, sense-making, and multiple iterations to resolve errors and inconsistencies in design and implementation (Penuel & Reiser, 2017). We will continue to mine the classroom data collected in other classrooms in order to identify additional pedagogical moves or heuristics that can guide curriculum development and science teachers actively adopting the new standards and fostering agentive learning.

**Conclusion**

The question this study seeks to initially answer is: how is learner agency best supported to foster more authentic, sustained, and valued science practices? Technology continues to afford new potential learning opportunities for producing and engaging with meaningful data, computational thinking and participation. The maker movement and citizen science initiatives more successfully motivate and engage participants in ways science education in schools does not (Barton & Tan, 2010). This project confronts the common drivers of time and standardized assessments to forge new potential pathways of ambitious science teaching (Windschitl, Thompson, & Braaten, 2018) toward nurturing agentive learners who can take more ownership of their science learning by producing their own data to analyze and learn from.

The approach is forging an upstream path confounded by material resistances such as sensor noise, poor Internet connectivity, and technical challenges as well as uncertainty with curricular innovations employing IoT and software tools used in support of agentive learning with data (Miller et al., 2018; Pickering & Guzik, 2008). It is designed to introduce greater learner agency, computational participation, and deepened facility with and understanding of data in today's high school science classrooms. For InSPECT biology activities, students are scientists: agentive data producers, doers of science — not reiterators of factual knowledge or history of science, nor re-creators of pre-designated strategies or procedures (as in “guided inquiry”). Students, like scientists, tinker and figure out each step along the way. However, teachers still play a key role facilitating and supporting agentive learners.

Where other teachers would likely feel drawn out of their comfort zone when getting silence upon asking students for their ideas about what they think their (messy) data results mean or indicate, or walking up to a lab group and seeing problems with the set-up and immediately joining in to troubleshoot, these educators avoid the temptation to move things along by reducing learner agency and instead sustain students’ epistemic agency in the classroom during times of uncertainty and confusion. They spend a bit more time supporting the natural surfacing of improved science practice or science knowledge. The results are positive and begin to suggest specific approaches and phrasing that both sustain learner agency and still reach needed results for learning within time constraints in a high stakes environment. Teachers can learn and adopt these new entry points to supporting and maintaining agentive learning.

Research on InSPECT implementations extends previous research demonstrating that science labs anchored in direct experience are more engaging for young scientists practicing their own experimental approaches. Adding opportunities for data production to learn about natural phenomena first-hand can begin to lead students toward more agentive behaviors with respect to scientific data. Learners utilize science practices to further their understanding of scientific concepts, develop scientific practice, and in the process, potentially develop greater interest in and skill for doing science.

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