Check for updates

Received: 28 May 2020 | Revised: 17 November 2022 | Accepted: 19 November 2022

DOI: 10.1002/tea.21841

RESEARCH ARTICLE

JRST | WILEY

Characterizing relationships between collective enterprise and student epistemic agency in science: A comparative case study

Jessica L. Alzen[1] | **Kelsey Edwards**[2] | **William R. Penuel**[1] | **Brian J. Reiser**[2] | **Cynthia Passmore**[3] | **Chris D. Griesemer**[3] | **Aliza Zivic**[2] | **Christina Murzynski**[2] | **Jason Y. Buell**[2]

[1]University of Colorado Boulder, Boulder, Colorado, USA

[2]Northwestern University, Evanston, Illinois, USA

[3]University of California Davis, Davis, California, USA

Correspondence
Jessica L. Alzen, University of Colorado Boulder, Boulder, CO 80309, USA.
Email: jessica.alzen@colorado.edu

Funding information
Carnegie Corporation of New York, Grant/Award Number: G-17-55086; Institute of Education Sciences, Grant/Award Number: R305B140042; James S. McDonnell Foundation, Grant/Award Number: 220020526

1 | INTRODUCTION

International science education reforms call for students to meaningfully engage in the practices of science and become active participants in developing and evaluating models and explanations as well as applying these ideas to answer their own questions about phenomena in the world (Berland et al., 2016; Erduran et al., 2018; Erduran & Dagher, 2014; Kawasaki & Sandoval, 2020; Manz et al., 2020; Miller et al., 2018). These calls reflect the epistemic values of the science community and contrast with more traditional approaches to teaching science that give students a narrow understanding of what it means to be a scientist because they fail to incorporate the epistemic, cognitive, and social elements of pursuing scientific knowledge (Erduran & Dagher, 2014). In particular, education reform draws on arguments that the pursuit of scientific knowledge should encourage collaborative engagement with the science practices, acknowledge individual background experiences and the influence those experiences have on how we pursue science, and recognize that diverse values in scientific inquiry promotes rich scientific knowledge (Carrier, 2013; Erduran & Dagher, 2014; Longino, 1990).

Student participation in the science practices is more than following directions to conduct pre-determined experiments and analyze data with expected solutions. Instead, students who

© 2022 National Association for Research in Science Teaching.

10982736, 2023, 7, Downloaded from https://onlinelibrary.wiley.com/doi/10.1002/tea.21841 by Northwestern University Libraries, Wiley Online Library on [08/11/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

engage in science practices develop questions and identify problems from phenomena. They then use the practices of science purposefully to build explanatory knowledge to address their questions and problems (Erduran et al., 2018; Erduran & Dagher, 2014). This requires classroom shifts that increase the *epistemic agency* of students (Damşa et al., 2010). That is, increase student involvement and authority in developing science knowledge and practices, rather than the teacher and textbook serving as sole sources of authority (Berland et al., 2016; Stroupe, 2014). This agency is *epistemic* in that students take on greater ownership and responsibility for making decisions on the direction and substance of building knowledge—identifying questions, exploring ways to address them, developing ideas, and reaching consensus. Attention to agency of this sort means that science disciplinary practices (i.e., the various ways the discipline of science uses to build, test, evaluate, and revise knowledge claims) must be integrated with students' ways of making sense. Further, the classroom community must value incorporating multiple perspectives and understandings as individual students integrate their own lived experiences into their enactments of the scientific practices as the community articulates principles for constructing and evaluating knowledge claims (Carrier, 2013; Erduran & Dagher, 2014; Longino, 1990).

Supporting teachers in these shifts requires (1) instructional materials designed to involve students in science and engineering practices; and (2) professional learning support for teachers in making these shifts (National Academies of Sciences Engineering and Medicine, 2018; National Research Council, 2015). We have explored a framework for instructional materials design and attendant professional learning supports, *purposeful sensemaking*, that aims to help students meet science learning goals while engaging them in meaningful science practices to address their questions and problems (Passmore & Svoboda, 2012; Penuel & Reiser, 2018; Reiser et al., 2021). Materials designed to support purposeful sensemaking present opportunities for teachers to engage students with puzzling phenomena that anchor the unit. Students develop questions they need to figure out to explain phenomena and identify problems they need to address. The curricular materials provide guidance for teachers to sequence phenomena, elicit emerging student questions, and support students' knowledge building to address the problems and questions students identified.

Working with instructional materials that support meaningful student engagement in science and engineering practices presents challenges for many teachers. Supporting student agency may require unfamiliar practices or may conflict with teachers' current pedagogical approaches (Wilson, 2013; Windschitl et al., 2008). For example, teachers need to center students' ideas and questions as well as support students in building explanatory models (Windschitl & Thompson, 2006). These approaches require supporting students in offering and negotiating ideas through classroom discourse that realizes the practices of argumentation, explanation, and modeling (Carrier, 2013; Michaels & O'Connor, 2012; Park et al., 2017). Teachers must focus on epistemic aspects of student thinking such as whether students' reasoning can be connected to class evidence, rather than solely evaluate the correctness of their conclusions (Berland et al., 2020; Kapon et al., 2018). To support all students as epistemic agents, teachers must also focus on the social dynamics of collective knowledge building (Erduran & Dagher, 2014; Longino, 1990). Teachers should help students identify where they agree and disagree by supporting students in connecting their ideas with those of their peers and provide opportunities for all students to weigh in on whether they are persuaded by the ideas of their classmates (Carrier, 2013; Krist & Suárez, 2018; Penuel & Watkins, 2019). We view these two elements of science knowledge building, epistemic agency and collective knowledge building, as central to teachers' work on achieving the goals of supporting their students' science practices.

10982736, 2023, 7, Downloaded from https://onlinelibrary.wiley.com/doi/10.1002/tea.21841 by Northwestern University Libraries, Wiley Online Library on [08/11/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

In previous work, we described how three teachers differentially create opportunities for students to act as epistemic agents and to engage in collective knowledge-building work (Alzen et al., 2020).[1] The descriptive nature of this previous research provided information about what variability can look like in classrooms attempting these reform-oriented pedagogical shifts. In this paper, we extend this prior work by presenting an expanded, but still exploratory analysis of how those three teachers, who participated in the same professional development community and were working with common instructional materials, attempted to support student agency through science practices in a common lesson. Our present goal is to use a multi-case study to identify emerging variations in key elements of knowledge and practice for inviting students' epistemic agency, even as teachers work toward specific learning goals. From these cases we advance the research by building theoretical conjectures that can be explored further in future work about how teachers' choices about collective knowledge building may yield differential opportunities for students to experience epistemic agency.

We leverage variation between enactments to explore tensions in enacting reforms. These shifts can be challenging for teachers who naturally interpret new reforms through the lenses of their current knowledge and practices (Spillane et al., 2002). Variations in how classrooms showcase these reforms can help identify the variety of potential tensions with current practice. Contrasting realizations of agency or collective enterprise can help identify those aspects of the reform that are not uniformly taken up and thereby suggest elements of the reform that present greater challenges. For example, perhaps providing opportunities for students to pose their own questions at the start of a unit emerges more consistently across classrooms, while using student questions to motivate target investigations appears more variable. The goal in the current study is to go beyond asking "to what extent did teachers take up a practice such as scientific argumentation" to a more nuanced analysis of how teachers interpreted and attempted to realize the practice in their classrooms. We use our unpacking of epistemic agency and collective enterprise to articulate these more nuanced questions about science practices. To do this, we investigate variations between classrooms in the apparent norms, participant structures, and resulting student activity. We examine how norms are communicated and reinforced through teachers' words and actions. How do teachers communicate to students that the "rules of the game" may be different from their prior experiences? How do teachers persuade students that their initial ideas are important to share, when much of their prior schooling may have led students to believe that they should only volunteer an idea that they are sure is correct? How do teachers convince students that they really mean this commitment to agency and collective enterprise, and it is not "just talk"?

2 | CONCEPTUAL FRAMEWORK

This work centers on two key ideas: epistemic agency and collective enterprise. We consider students as epistemic agents when they "take, or are granted, responsibility for shaping the knowledge and practice" (Stroupe, 2014, p. 488). We define *collective enterprise* as a commitment to "collaborative idea production" among all members of the community (Damşa et al., 2010, p. 152). We argue that exploring variations in opportunities for students to act as epistemic agents is enhanced by looking for evidence of a commitment to a collective enterprise.

In principle, these two ideas need not go together. Students could be active epistemic agents in identifying questions, investigating them, and making sense of what they uncover as

10982736, 2023, 7, Downloaded from https://onlinelibrary.wiley.com/doi/10.1002/tea.21841 by Northwestern University Libraries, Wiley Online Library on [08/11/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

individual or even competitive agents. However, there are strong reasons to look for connections between these ideas in classrooms supporting science practices. First, building knowledge in science is a social practice involving sharing, critiquing, and negotiating ideas (Ford & Wargo, 2012; National Research Council, 2012; Osborne, 2014). Second, design research identifies the social context for building and revising ideas as a key element of ambitious disciplinary work (Bielaczyc & Collins, 1999; Brown & Campione, 1990; Engle, 2012). A community of learners provides a context in which the process of participants sharing their thinking gives opportunities to draw on the diversity of ideas, consider alternatives, and reach a consensus (Carrier, 2013; Longino, 1990). Such a community can also create an emergent need for scientific argumentation. In this section, we identify key elements of epistemic agency, collective enterprise, and their relationship. We also describe how we investigate the interplay between these ideas in our multiple-case studies.

2.1 | Epistemic agency

Pedagogical shifts to support epistemic agency are needed to achieve the central task of engaging students in the practices of building and refining knowledge (Ford & Forman, 2006). When teachers create environments that empower students to act as epistemic agents, students are partners in the intellectual work of building, testing, and revising ideas, rather than passive recipients of information (Damşa et al., 2010; Miller et al., 2018; Scardamalia & Bereiter, 1991).

Several interrelated elements are involved in students taking on more epistemic agency (Engle & Conant, 2002). One aspect is classroom *tasks*. Rather than being provided explanations by teachers or textbooks, students engage in tasks structured so that they work with phenomena, identify questions, attempt to make sense of the phenomena by investigating those questions, and take a central role in developing explanations (Lehrer & Schauble, 2006). In addition, *participant structures* need to support these shifts in students' expectations about their roles and authority (Cazden, 2001; Engle & Conant, 2002; Stroupe, 2014; Tabak & Baumgartner, 2004). *Classroom discourse* plays a key role in this work as it is a mechanism for sharing, critiquing, and negotiating ideas. Teacher support for this discourse is critical as students respond to the messages teachers share about student roles in the classroom (Ke & Schwarz, 2021). Teachers need to support students in listening to and building on one another's ideas (Michaels et al., 2008; Michaels & O'Connor, 2012; Park et al., 2017) and to create environments in which students take responsibility for engaging with ideas as they are developed, used, and refined by the community in order for students to take up epistemic agency (Berland et al., 2020; Levrini et al., 2019; Russ, 2018).

2.2 | Collective Enterprise

Shifts in tasks, participant frameworks, and discourse are also needed to foster an environment where students see classrooms as communities of learners in which they build knowledge together with their teachers (Bielaczyc & Collins, 1999; Brown & Campione, 1996; Herrenkohl et al., 1999). We observe a commitment to a collective enterprise when teachers support students in exchanging ideas with others as well as through cycles of identifying questions, negotiating how to investigate them, and making sense of what they found as a group. The presence of multiple approaches to a phenomenon and attempts to reach consensus while making sense of those variable ideas are central to a classroom committed to a collective enterprise (Carrier, 2013). Teachers play a key role in supporting a learning community that is intentionally organized to build knowledge collaboratively (Scardamalia & Bereiter, 1991), helping students draw on science discourse practices to explore competing ideas, engage in principled and public argumentation, and reach consensus about ideas (González-Howard & McNeill, 2019; Reiser et al., 2021). Such communities are also characterized by the appropriation of common tools such as public representations to record the community's knowledge-building work that provides a shared resource for participants to draw upon (McGinn et al., 1995).

2.3 | Characterizing inviting and actualizing in epistemic agency and collective Enterprise

We ground our approach by distinguishing offering and taking up within epistemic agency and collective enterprise. Engle et al. (2014) suggest that conversations involve "bids," or the proposal of ideas from one individual, drawing on Sacks et al.'s (1978) model of bids to enter a conversation. Bid ideas can be "taken up," changed, ignored, or rejected by others. In our analyses, we adapt these ideas to consider how teachers invite and support student contributions in classroom discourse. We analyze how teachers make bids or "invite" *students* to contribute ideas. If students take up these bids to contribute, we consider the extent to which teachers then take up or "actualize" student ideas in response. Our particular interest is in how and to what extent teachers attempt to establish classroom norms to pursue a commitment to a collective enterprise and opportunities for students to act as epistemic agents (Engle et al., 2014; Sacks et al., 1978). Distinguishing inviting from actualizing enables us to tease apart when teachers "talk the talk" and suggest these shifts to students from when they also deliver on those promises. In other words, to identify when teachers continue to prompt for and act on student contributions to support students' agency and collective work as opposed to simply promising as such.

We characterize inviting epistemic agency as when teachers ask students for their ideas and tell students they have responsibility for making decisions (e.g., "You need to share your ideas so we can decide where to go next") (Damşa et al., 2010; Miller et al., 2018; Scardamalia & Bereiter, 1991). This invitation positions students to share authority with teachers (Michaels & O'Connor, 2015; Tabak & Baumgartner, 2004). In actualizing epistemic agency, the teacher *acts* on students' ideas (e.g., "Marcus suggested we collect more data, so we're going to do that next") and shares authority with students to make decisions (e.g., "Which of these investigation ideas should we pursue?"). We separate invite and actualize because teachers may invite student ideas, but eventually tell students what happens next instead.

Inviting collective enterprise comprises encouraging norms for collective knowledge building such as asking students not only to speak but to listen and build on others' ideas, or stress appropriate physical orientation for listening to others (Michaels et al., 2008; Michaels & O'Connor, 2012; Park et al., 2017). Actualization happens when the teacher facilitates that joint work (Bielaczyc & Collins, 1999; Brown & Campione, 1996; Herrenkohl et al., 1999). Examples of this are when teachers make all student ideas public, encourage students to evaluate the ideas of others, or leverage disagreement to highlight gaps in the sensemaking process (González-Howard & McNeill, 2019; Reiser et al., 2021). This contrasts with evaluating individual student ideas as correct or not or identifying the correct answer when students disagree and moving on. Teachers also actualize a commitment to the collective enterprise when they indicate they are learning alongside students, positioning themselves as co-constructors of

10982736, 2023, 7, Downloaded from https://onlinelibrary.wiley.com/doi/10.1002/tea.21841 by Northwestern University Libraries, Wiley Online Library on [08/11/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

knowledge rather than authoritarian sources of information, illustrative of partner participant frameworks and symmetry in the classroom (Tabak & Baumgartner, 2004).

We suggest that epistemic agency and collective enterprise are central characteristics in making science and engineering practices meaningful in classrooms. However, these constructs include aspects that are broader than science practices. The role of students as knowledge builders in a variety of academic disciplines has been proposed in the work on productive disciplinary engagement (Engle, 2012; Engle & Conant, 2002), cognitive apprenticeship (Collins et al., 1989), and others. The utility of viewing knowledge building as within a community has been characterized in work on academic talk (Michaels et al., 2008; Park et al., 2017) and learning communities (Bielaczyc & Collins, 1999; Brown & Campione, 1994). We view the work of supporting student epistemic agency in science as drawing on goals that are broader than science, such as creating classroom norms where students feel that they are responsible for making decisions about what questions to pursue and how to pursue them. However, the form that these supports take, and the specific criteria used to make these decisions, can and should be informed by the discipline of science. For example, the idea of students raising questions and finding gaps in the classroom's current understanding is relevant across disciplines. But the criteria used to evaluate whether a question is productive scientifically or a science explanation is adequate are science-specific strategies (Carrier, 2013). We return to this notion when considering how epistemic agency and collective enterprise appear in various forms in our classroom cases.

3 | A MULTIPLE-CASE STUDY OF EPISTEMIC AGENCY AND COLLECTIVE ENTERPRISE

In this study, we explore the connections between inviting and actualizing epistemic agency and collective enterprise and posit that the interplay between these constructs can influence students' classroom experiences. To that end, we investigate two research questions:

1. What variations do we observe in classroom enactments in how teachers support a collective knowledge-building enterprise and student epistemic agency?
2. How do the differential support for inviting and actualizing a collective knowledge-building enterprise and opportunities for student epistemic agency appear to influence student engagement in knowledge-building work?

The goal of this study is to explore the potential relationship between these constructs as teachers and students make sense of these ambitious reforms. We aim to develop evidence-informed conjectures about their interaction to inform future research with more comprehensive analyses, rather than testing causal connections between teacher support and forms of epistemic agency.

4 | DATA AND METHODS

To examine teachers in the process of grappling with shifts in their teaching to support students in science practices, we conducted a multiple-case study (Yin, 2017) of three teachers drawn from a larger study investigating the beliefs and practices that influence how science teachers enact curriculum materials. Teachers in the larger study were recruited based on a minimum of 3 years of science teaching experience and prior professional learning related to the Next Generation Science

10982736, 2023, 7, Downloaded from https://onlinelibrary.wiley.com/doi/10.1002/tea.21841 by Northwestern University Libraries, Wiley Online Library on [08/11/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Standards. All teachers attended a week-long professional development institute in summer 2018 that utilized curriculum materials designed to support purposeful sensemaking. Teachers also participated in a virtual professional learning community that met approximately every 2 weeks via videoconference during their teaching of two target units in the 2018–2019 school year.

4.1 | Teacher and student participants

We selected teachers for this analysis based on our interest in theory development. To develop theory from case studies, investigators can choose cases that are expected to replicate patterns predicted from well-articulated theories (e.g., Yin, 2017), or to provide contrasting cases for the purpose of theory of elaboration (e.g., Eisenhardt, 1989). Our purpose was the latter, and we chose teachers whose approaches to inviting epistemic agency and collective enterprise differed, so that we might elaborate a theory for how these differences might influence students' opportunities to learn science.

The variation among these three teachers in the ways they supported student agency and focused on learning as a collective endeavor became evident during initial data analyses for our larger research study. This initial analysis involved reviewing transcripts of multiple teachers' classroom discussions, from which we selected these three teachers because they appeared to engage students differently in discussing science ideas and phenomena. To investigate this variation more deeply, we conducted an analysis to see if this variation was evident in contrasts between teacher moves in conversation to illustrate a theoretical relationship between epistemic agency and a commitment to a collective enterprise (Engle et al., 2014; Flyvbjerg, 2006; Sacks et al., 1978; Yin, 2017). Like other comparative case studies of this kind (e.g., Carlone et al., 2011; Windschitl et al., 2020), we hoped to identify key ways teachers support particular forms of student participation, in our case, purposeful sensemaking.

All three teachers taught sixth grade in the Midwest region of the United States. Ms. Falconeri,[2] whose disciplinary background is in elementary education, taught in a suburban school and had been teaching for 7 years at the time of this study. Her school served predominantly White (57%) and Asian (38%) students. Over 80% of the students at her school were proficient on state standardized tests in math and English Language Arts during the year this study took place. Ms. Taub, who also studied elementary education, was in her 11th year of teaching during this study. She taught in an urban school that primarily served White (63%), Latinx (13%), Asian (9%), and multiracial (9%) students. Just over half of the students in this school were proficient in math and English Language Arts during the year this study took place. Finally, Ms. Thornhart, whose disciplinary background is in biology and conservation, was in her 18th year of teaching when these data were collected and taught at another urban school that served primarily White (52%), Latinx (22%), and Asian (22%) students. Approximately 60% of the students in this school were proficient in math and ELA during the 2018–2019 school year.

4.2 | Curriculum materials context

All three teachers in this study implemented the same middle school storyline-based curriculum unit, "How can we produce a bunch of fog for a spooky scene?" (the fog unit). Storyline units are designed to support students in meeting target learning goals while simultaneously involving students in partnering with teachers to manage the trajectory of the classroom's

10982736, 2023, 7, Downloaded from https://onlinelibrary.wiley.com/doi/10.1002/tea.21841 by Northwestern University Libraries, Wiley Online Library on [08/11/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

sensemaking (Next Generation Science Storylines, 2018; Reiser et al., 2021). Storyline units begin with an engaging and puzzling anchoring phenomenon that teachers use to elicit student questions about how and why the phenomenon occurs. Teachers support students in working with their questions to plan and conduct investigations, make sense of what they find, and to incrementally build explanatory accounts of the phenomena.

The fog unit is organized around the design challenge of creating fog for a spooky scene for the classroom. To figure out how to develop a homemade fog machine, students raise questions about what fog is made of and the conditions needed for its formation. Students investigate weather data and conduct hands-on experiments with temperature and humidity to figure out how fog forms and apply that scientific knowledge to inform their iterative design of their fog machines. The unit is designed to support students in developing a mechanistic model of temperature change and fog formation, the general kinetic molecular theory that underlies this model, and practices of engineering design as they construct a fog machine meeting their criteria and constraints. The teachers spent between 10 and 14 weeks enacting this unit.[3]

We selected lesson 9 of the 14-lesson unit as the focal lesson for this analysis. Prior to the focal lesson, students figured out that water vapor becomes liquid when temperature cools, and when there are enough small particles of matter in the air, such as dust or smoke, the water condenses on these particles (called cloud condensation nuclei—"CCNs") to make fog. The class attempted to add CCNs to the air by throwing things into the air and by boiling liquids containing CCNs, but they were unsuccessful. The class then decided to investigate what happens to substances when they are heated and cooled that might explain why their fog was not working. In lesson 9, students investigate how heat influences particle movement in water and then consider whether the same interaction of heat and particle movement is true for air.

We chose this lesson because it poses challenges for teachers in using student ideas to plan investigations and make sense of their findings. Our data come from the opening whole-class discussions (∼15 min) where we observed how teachers navigate the tension between their interpretation of the curriculum, their plans, how they facilitate the discussion, and students' developing thinking. These discussions were designed for teachers to support student epistemic agency, and we found it a rich context to explore variation in how teachers chose to invite and actualize epistemic agency and collective enterprise.

Due to last-minute pacing changes at the scheduled recording dates, our first teacher's class was at the beginning of this lesson and just starting the work of investigating temperature, and the remaining teachers' classes had already uncovered something about temperature in water and were considering if the same holds true for other substances. In the videos used in this study, the classes discuss how temperature influences particle behavior in different contexts. Although the teachers are in slightly different places in the lesson, the videos provide similar settings for investigating the interplay of opportunities for epistemic agency and collective enterprise.

4.3 | Approach to analysis

We set out to identify variability regarding the ways teachers supported epistemic agency and collective enterprise through discourse and to build conjectures about patterns between those constructs (Engle et al., 2014; Sacks et al., 1978; Yin, 2017). As such, our analysis included iterative deductive and inductive coding. We began by broadly coding turns of talk in video transcripts for any evidence of either collective enterprise or epistemic agency as defined in our conceptual framework. Specifically, we looked for moments when students took or were given

10982736, 2023, 7, Downloaded from https://onlinelibrary.wiley.com/doi/10.1002/tea.21841 by Northwestern University Libraries, Wiley Online Library on [08/11/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

responsibility for directing knowledge building and/or classroom practice (Stroupe, 2014). We also identified when the class engaged in "collaborative idea production" (Damşa et al., 2010, p. 152). This first step was to identify any substantive evidence of both constructs across all three transcripts. From there, we expanded our codebooks inductively to capture nuance within each construct so that we could better characterize observed variability. This expansion was also based on prior literature and our own previous work with these data (Alzen et al., 2020). Table 1 summarizes the ways we coded how teachers invited and actualized student ideas within the constructs of epistemic agency and collective enterprise.

These codes enabled us to tease apart when teachers explicitly invite students into the targeted nature of the work from when teachers implement work motivated by student ideas, a contrast we identified as a key point of variability between teachers. Once our codebook was finalized, we engaged in a collaborative and iterative process of recoding, identifying patterns and comparing across team members until we reached consensus (Cresswell, 2013). Next, we purposefully juxtaposed coding summaries of each case with one another, which—as often happens in comparative case analyses (c.f., Eisenhardt, 1989)—resulted in new concepts that we did not anticipate ahead of time. Comparative case analysis of coding from our initial sensitizing constructs (Bowen, 2006) of inviting and actualizing epistemic agency and collective enterprise led to the emergence of three new characterizations of opportunities for students' enactment of epistemic agency (directed

TABLE 1 Summary of coding scheme for epistemic agency and collective enterprise

	Invite		Actualize	
	Definition	**Example**	**Definition**	**Example**
Epistemic agency	Teacher encourages students to share ideas, questions, and explanations, regardless of correctness or completeness of ideas.	"Your ideas are important for how to figure this out." "Remind me why we are interested in temperature so much."	Teacher uses student ideas to motivate discussion and/or next steps in classroom activity.	"You said we need to investigate temperature, so that's what we are doing next." "We did exactly what you said you wanted to do next."
Collective enterprise	Teacher encourages behaviors that support student engagement with one another's ideas for the purpose of collective knowledge-building.	"Face this way. It's important that we all hear so we can think together." "Give me a thumbs up or thumbs down. Everybody has to have a thumb because you are either on board, disagreeing, or unsure."	Teacher facilitates conversation such that teacher and students take up joint work of collective knowledge-building.	"I do not know. I'm figuring this out with you guys. What do you think?" "Somebody who is not totally convinced of this, can you let us know what you are thinking so we know what we need to do to make sure we agree?"

10982736, 2023, 7, Downloaded from https://onlinelibrary.wiley.com/doi/10.1002/tea.21841 by Northwestern University Libraries, Wiley Online Library on [08/11/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

10982736, 2023, 7, Downloaded from https://onlinelibrary.wiley.com/doi/10.1002/tea.21841 by Northwestern University Libraries, Wiley Online Library on [08/11/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

agency, framed agency, and consensus-motivated agency), which we present next in our results. For each case we first summarize patterns in how each teacher supported epistemic agency and collective enterprise. Following the three cases, we compare the approaches and consider the implications for students' experiences with science practices.

5 | RESULTS

To present our results, we show contrasting descriptions of the ways each teacher orchestrated the opening class conversation. To be clear, each of the cases include elements of inviting and actualizing both collective enterprise and epistemic agency. We use these cases to present qualitative differences that emerged from our analysis and theorize how the nuanced variability in collective enterprise may yield different opportunities for agency for students as has been called for in prior literature (c.f. Miller et al., 2018). Since our emergent theory focuses on variability in resulting opportunities for agency, we label each case for ease of reference as directed agency, framed agency, and consensus-motivated agency.

In the next section, we walk through key excerpts to illustrate the patterns we see in these discussions. We offer these cases not as exhaustive classification of the range of agency we expect to see across science classrooms, but rather as an initial approach to capture some important differences in how attempts to achieve these reforms can play out, identifying conjectures to be taken up in theory development (Yin, 2017). We present the cases in order of apparent attention to collective enterprise to best highlight differences. That is, we suggest that the extent to which a teacher attends to actualizing the collective nature of knowledge-building work is one way by which we can examine opportunities for student epistemic agency.

5.1 | Case 1: Ms. Falconeri—directed agency

Recall that our first teacher, Ms. Falconeri, is just beginning the process of investigating temperature with her students. In this opening conversation, she follows the curriculum rather closely in that she facilitates a conversation in which she reminds students of what they did yesterday and in previous lessons in order to make a plan for what to do next. This teacher makes the fewest changes to the lesson in the curriculum materials out of the three teachers presented.

Ms. Falconeri starts class with a summary what the class discovered in previous lessons. Then she invites epistemic agency with a question:

> *Ms. Falconeri*: We could not get CCNs into the air even though we tried really, really, really hard and we did a million things and you guys had so many phenomenal ideas. I was so impressed! But nothing worked. [...] So, what are we missing? What do we need to think about next? Jagger, can you share what you were sharing with me? What do you think we need to think about next, Jagger?
>
> *Jagger*: Um why the water is not clumping to the CCN maybe other components such as temperature.
>
> *Ms. Falconeri*: Ok, so Jagger said we need to figure out how to get the water to clump onto those CCNs. He thinks it's something to do with temperature.

Ms. Falconeri starts by naming students as the source of ideas in the class ("*you* guys had so many phenomenal ideas") and as knowledge-building partners ("So, what are *we* missing? What do *we* need to think about next?"). In reminding the students of their previous investigations about CCNs and then asking for their ideas about what to do next, Ms. Falconeri shows how the students have been agentive and invites them to work alongside her in figuring out science ideas. In doing so, she engages students in the practice of asking and refining questions of their own previous science ideas to help with explanations of the natural world. After her invitation to agency with a question, Ms. Falconeri immediately calls on a specific student to share, signifying the student's idea is worthy of consideration by the class. Notably, although the idea was from students, Ms. Falconeri guided the class by naming which student should share. Jagger suggests the class should consider temperature (which is the next step defined in the curriculum). Ms. Falconeri then calls on three other students with their hands up to share their ideas about what to do next. For each of the three students, Ms. Falconeri follows a pattern: she calls on the student, restates their response, and calls on the next student without evaluating, making connections, or elaborating. Instead, she allows for multiple voices to be heard free from her own reactions. Two of these students mention temperature as Jagger did, and one voices the idea of investigating specific kinds of molecules or CCNs in the air. By providing space for multiple student ideas without comment, Ms. Falconeri gives more students the opportunity to have their voices heard and considered by others in the room.

After the third student shares, Ms. Falconeri refers to the "Driving Question Board" (DQB) where the class keeps a public record of their questions (Weizman et al., 2008).

> *Ms. Falconeri*: So it sounds like temperature is something that we feel like we need to investigate, and if I go back to our Driving Question Board over here. I remember a ton of questions saying like "what is the ideal temperature for fog to form?" We asked questions like "how does water clump together?" So we are still thinking about that. There is a question, "how can fog form at thirty degrees and seventy degrees?" So we definitely have been wondering about temperature for a long time. Who can remind me why were we even interested in temperature in the first place? Shiloh?
>
> *Shiloh*: I think it was from when we took samples from different cities across the United States, and we looked at how their places had fog. The temperatures that they experience.
>
> *Ms. Falconeri*: I agree with Jagger and Shiloh. I think temperature is something we have not looked into yet, but we have been really curious about for a long time.

Ms. Falconeri uses the DQB as another method to remind students about their previous questions about temperature and to revisit how they generated those questions. Shiloh's comment helps the class remember that they previously looked at weather data together, and some members of the class wondered about how temperature might influence fog formation. As Ms. Falconeri next leads the class to investigate temperature, she actualizes an opportunity for epistemic agency for those students who asked about temperature on the DQB and those who recognize that understanding temperature is a potentially productive step in the class investigations.

To begin this work with temperature, Ms. Falconeri asks the class to talk in their groups about what they think happens at the molecular level when water and air get hot. When they return to whole class discussion, Ms. Falconeri comments about the variety of student ideas she heard while circulating in the room. She then surfaces one in particular:

10982736, 2023, 7, Downloaded from https://onlinelibrary.wiley.com/doi/10.1002/tea.21841 by Northwestern University Libraries, Wiley Online Library on [08/11/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Ms. Falconeri: I'm hearing some crazy theories that I'm wanting to test. So, Table 2, Althea had an idea, and I pushed them, and now they have another idea, and I really want to test this idea. So, Althea, what do you think happens to water as it gets hotter?

Althea: It's the molecules start moving faster and faster.

Ms. Falconeri: Faster and faster. So like, they are not moving at all and as they get hot they start moving. Is that what you are thinking?

Althea: No. They'll move a little unless they are frozen because they are solids and they are not moving when they are solids.

Ms. Falconeri: Ok and then as they get hotter you think that they move faster?

Althea: Yeah

Ms. Falconeri: Does anyone have any other, any thoughts about that? Does anyone else agree, disagree with Althea? Provide their thoughts?

Like before, Ms. Falconeri asks Althea to share her idea, and then Ms. Falconeri clarifies and explores Althea's ideas rather than add or interject her own thoughts. Ms. Falconeri invites students to build upon Althea's idea and encourages collective work ("Does anyone else agree, disagree with Althea?"). In response, two students share ideas about putting something into the water to see if what Althea shared can be observed. These contributions move the class toward refining their working model of the particle nature of matter as well as planning an investigation to test their developing model. In response, Ms. Falconeri transitions the class with the following statement:

Ms. Falconeri: We're going to figure out how we can visualize this, and I think I have an idea. Althea said that hot water and cold water are moving differently. Right, Althea? You still agree with that? I want to see that. So if you would like to, you are welcome to join on the carpet for demos.

There is a slight shift in language here that characterizes the type of opportunities for agency occurring in this episode. As before, Ms. Falconeri selects the idea that gets taken up, but she is explicit about it in this comment ("I think I have an idea…I want to see that."). While Ms. Falconeri indicates that she has an idea for how to visualize what's happening at the molecular level, she connects this idea with the issue Althea brought up. Thus, while guided by the teacher, the next steps are still connected to student-generated ideas. Ms. Falconeri indicates they are working together, teacher and students, to collectively visualize how water molecules act when heated and test their hypotheses about the influence of temperature on particulate matter.

5.2 | Agency in Ms. Falconeri's classroom

Ms. Falconeri supports both collective knowledge-building efforts and student epistemic agency at multiple points in the opening class discussion. We consistently see Ms. Falconeri invite agency by asking students to provide direction with comments such as "What are we missing?

10982736, 2023, 7, Downloaded from https://onlinelibrary.wiley.com/doi/10.1002/tea.21841 by Northwestern University Libraries, Wiley Online Library on [08/11/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

What do we need to think about next?" In this way, the teacher positions herself alongside students in the knowledge-building process and privileges student ideas in class conversation, encouraging them to take agency. Ms. Falconeri also strategically actualizes agency for Jagger's idea, connecting it to previous student ideas on the DQB. By elevating student ideas she knows will move the class forward in productive ways, Ms. Falconeri guides the flow and direction of conversation in a way that both allows for the class to make progress and for students to see their ideas at the center of their work. We name this pattern in teaching as *directed agency*. It supports agency in that student ideas are the ones used in class. At the same time, the teacher plays a large role in guiding which specific ideas are taken up.

Directed agency is one way that teachers can navigate the tension between supporting student sensemaking and moving through curriculum. From this excerpt, we posit that by taking up student ideas in the class discussion, Ms. Falconeri actualizes epistemic agency opportunities for multiple students in the class. The idea that something was missing from their models came from the students' recognition that their designs were not working to make fog. The idea that temperature has something to do with it came from several students during the class, and Ms. Falconeri tied this back to earlier questions that were captured on their DQB.

The directed nature of the work may limit some aspects of agency in classrooms. Recall that immediately after Jagger suggests temperature as a next step, another student suggests that the particular CCN or molecule in the air might be important. Ms. Falconeri chooses not to act on this idea, a point of variability from the other cases we consider next. Instead, she restates the student's idea along with several others without additional comment. Furthermore, when Ms. Falconeri refers to the Driving Question Board, she revisits those questions related to temperature, while other ideas were present on the board as well. Although not all students see their specific ideas taken up by the class, Ms. Falconeri does not explicitly state that some ideas are correct while others are not. Instead, she provides space for students to share and acknowledge one another's ideas, and then directs the conversation toward specific student ideas.

5.3 | Collective enterprise in Ms. Falconeri's classroom

While Ms. Falconeri plays a strong role in amplifying ideas she knows will take the class in the direction she wants, she frequently states publicly that she is co-constructing knowledge with her students. She reminds them that the ideas taken up by the class all come from them (e.g., "We asked questions like "how does water clump together?"). She provides multiple opportunities for more than just the ideas she elevates for the class to be made public through small group discussions and explicit requests for students to share and build upon others' ideas (e.g., "Does anyone have any other thoughts about that?"). Commitment to a collective enterprise is evident at multiple points in Ms. Falconeri's class. However, this is primarily with a focus on co-construction of knowledge between the teacher and the students and less focus among students themselves.

In sum, Ms. Falconeri works to create a classroom culture in which students have opportunities to see themselves as co-investigators with their teacher. The ways that Ms. Falconeri carefully selects which ideas to open up for whole group discussion appear key to how she manages the tension between supporting students in their sensemaking and keeping the class on track to curricular goals. We next look at a case where variation in supporting a collective enterprise provides evidence of another potential characterization of student epistemic agency.

10982736, 2023, 7, Downloaded from https://onlinelibrary.wiley.com/doi/10.1002/tea.21841 by Northwestern University Libraries, Wiley Online Library on [08/11/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

5.4 | Case 2: Ms. Taub—framed agency

The day before our observation of the focal lesson in Ms. Taub's class, the students figured out that heat causes water particles to move faster and take up more space. Ms. Taub adapted the designed lesson that motivates the next day's opening conversation by assigning a Google survey homework assignment. She asked students to indicate if they thought the effects of heat on water particles would also be the same for air particles. She also asked them to propose ways to investigate whether this was true or not.

At the start of class, Ms. Taub asks students: "remind me why we're interested in temperature so much?" This actualizes collective enterprise as Ms. Taub identifies herself as co-constructor of knowledge with the students. When students answer, Ms. Taub consistently actualizes collective enterprise through questioning.

- "What do you guys think about [what Manny said]?"
- "Can anyone build on his idea?"
- "Can someone maybe connect back to Sheila's idea?"

Ms. Taub asks students to make sense of their ideas alongside the ideas of others—supporting students in collective knowledge-building work as well as engaging the class in regular reconsideration of their models for molecular behavior.

Seven students contribute to the review of what led them to try to figure out temperature. They describe how they were unable to create fog just by adding CCNs to the air and decided that the connection between temperature and fog noticed earlier in their weather data might be relevant. Ms. Taub's next move creates opportunities for both collective enterprise and epistemic agency.

> *Ms. Taub*: Last night for your homework, I asked if you think that what happens to water also happens to air… Out of everyone who did their homework, 84% of you actually said yes, what happens to air molecules is exactly like what happens to water molecules. And then we had like 16% of those people who did their homework say, no, air does not respond the same way. So because we have some discrepancy for what we think happens to particles like air, I asked you for investigation ideas. And I screenshotted them from the Google forms this morning and you gave me some inspiration.

By projecting all their homework responses, Ms. Taub gives space for each student's ideas to be entertained by the class and allows students the opportunity to see how their ideas for investigation compare to ideas offered by others, a key element of collective knowledge building. Next, Ms. Taub facilitates a conversation about which investigation ideas the class should take up in order to further refine their model of the influence of temperature on air and water particles.

> *Ms. Taub*: People were saying turn a bunch of fans on, and the air conditioning, try to make it cooler or hotter. People actually talked about confining air or trapping air. Do you think if we just heated our classroom, we'd actually be able to see what happens? Or do you think we would actually need to contain the air?

10982736, 2023, 7, Downloaded from https://onlinelibrary.wiley.com/doi/10.1002/tea.21841 by Northwestern University Libraries, Wiley Online Library on [08/11/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Marissa: Contain the air, because it would take not as long, it would take longer to make the whole entire room a certain temperature than it would be to make a smaller thing a certain temperature.

Ms. Taub: Wait. So you are saying if we heated our whole room it would be too hard, but if we heated a small amount of air it would not take as much time? What do you guys think about that?

Ms. Taub begins by taking up two broad ideas from the list of suggested investigations (e.g., heating and cooling the room vs. heating and cooling trapped air). On one hand, this is similar to Ms. Falconeri in that Ms. Taub selects specific ideas from the list for discussion. On the other hand, Ms. Taub's broad categories encompass ideas from many students. It may be that multiple students in Ms. Falconeri's classroom agree that temperature is the next logical step for investigation. However, Ms. Falconeri's directive practices do not encourage students to make that potentially collective thinking as public as Ms. Taub's discussion. Furthermore, Ms. Taub's initial statement does not take a position on the open room versus trapped air question. It is a student, Marissa, who suggests containing air would be helpful. At this point several students agree with Marissa, at which point Ms. Taub also agrees, and asks students to consider how:

Ms. Taub: Yeah like I mean oh my gosh if we heat the whole classroom that would be really hard to see, right? So I like the idea of confining it. Could anybody find up here [at the front of the room] something that could actually contain the air though?

Angelique: Um maybe we could use like a bin. We could turn it over and we could trap the air inside of that.

Ms. Taub: So like I trap the air in the bin and then I'm going to heat the bin?

Angelique: No

Ms. Taub: We could [trap air in a bin]! I do not know. I'm trying to figure this out with you guys. Like if we just trap it in a bin, would I be able to see what happens to the air inside if I heat the air?

In this way, Ms. Taub invites epistemic agency by asking students to figure out what they could use to trap air. Then she invites agency and actualizes collective enterprise by suggesting the idea to the whole group. Ms. Taub identifies herself as a learner alongside her students ("I'm trying to figure this out with you guys"), reminding students of the collective nature of their work. She eventually endorses the idea of trapping air, but only after several students agree and no students argue for the alternative.

Ms. Taub: Can we go on [with] this idea though of trapping air? What are some other things that I have in the classroom that maybe could trap air in it that we could like totally see and we know that there's air inside? There are ideas up here that people gave. We've got to figure out which ones we want to do.

10982736, 2023, 7, Downloaded from https://onlinelibrary.wiley.com/doi/10.1002/tea.21841 by Northwestern University Libraries, Wiley Online Library on [08/11/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Serena: Balloon

Ms. Taub: Why?

Serena: Um, we could just pump air in it.

Ms. Taub: Yeah. Totally. We could put air in the balloon, and we know that there's air inside, seal it. Right? What could I actually do with that balloon to see what happens to air when I heat it and cool it?

Lucky: Hair dryer

Ms. Taub: Oh yeah yeah yeah. Ok cool. We could heat it up with a hair dryer. What if I wanted to make the air in the balloon cold?

Sharise: Put it in the freezer

Ms. Taub: Put it in the freezer. Well guess what? People here literally said [to do that on the Google forms] .... There's a lot [of ideas] to try to capture the air, or contain the air. There's a lot of people who had thought let us actually get the air in something. ... So here's the deal, last night when I was reading these, I actually took this [balloon] idea into consideration. I actually did exactly what you guys wanted me to do. I actually stuck the balloon in the freezer. Then I pulled it out of the freezer, and we are going to see what happens to it. ... I have a video for you of me actually taking a balloon, sticking it in the freezer, and seeing what happens to it when I pull it out.

Ms. Taub pushes ahead with the idea of capturing air as multiple students suggest. A student proposes a balloon, and Ms. Taub asks the student to explain her reasoning. Thus, even though Ms. Taub reveals she already acted on these ideas and conducted a test of cooling trapped air, she guides a discussion in which students assemble the reasoning that motivates conducting this test. By following through with the idea of trapping air in the balloon, the class is able to consider a potential mechanistic explanation to the phenomenon.

5.5 | Comparing Ms. Falconeri and Ms. Taub's approaches to agency

During the lesson, we see Ms. Taub's consistent support of collective knowledge-building efforts and student epistemic agency to plan and carry out an investigation. A salient feature of this episode is Ms. Taub's use of projected student homework responses to frame conversations. In some ways, Ms. Taub directs student agency through this projection in ways not all that different from Ms. Falconeri. However, the directive nature of Ms. Taub's work is more open-ended than Ms. Falconeri's. Ms. Taub determines the general topic of class discussion via a common artifact generated by the class community and uses that same artifact to provide opportunities for students to experience epistemic agency. In the homework, she explicitly asks students for investigation ideas to explore how molecules behave differently in air and water. The resulting conversation not only allows students to plan an investigation, but it also allows them to consider questions they must address in that investigation. Although Ms. Taub did act on a selection of

10982736, 2023, 7, Downloaded from https://onlinelibrary.wiley.com/doi/10.1002/tea.21841 by Northwestern University Libraries, Wiley Online Library on [08/11/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

student ideas, these were common themes among students. And before revealing the experiment she conducted, she has students work through the reasoning about how this would help. The framed conversation helps direct the class, but also allows for students' ideas to be made public and enables them to participate in working through the reasoning for this next step. We name this pattern *framed agency* as the teacher frames the classroom conversation in specific ways, but she allows for students to direct the conversation within the provided context.

Students have opportunities for agency in both Ms. Falconeri and Ms. Taub's classes. The science ideas being constructed and directions for next steps are connected explicitly to students' ideas. Yet there are also some limitations on how agency is realized in both classrooms. A similarity between Ms. Taub and Ms. Falconeri is elevating some student ideas over others. Although not as explicit, Ms. Taub privileges the idea of trapping air. The homework question asked for investigation ideas to understand whether air and water molecules act the same way. Ms. Taub only brings up ideas that focus on trapping air molecules and does not entertain the few divergent ideas (e.g., investigating steam and ice, heating and cooling "other" substances; See Table S1 for full list). For some students, these other ideas may make more sense as a next step. It might also be the case that although these were their initial ideas, these students may have been convinced that trapping air of different temperatures would be a logical next step. However, students were not given the opportunity to discuss this together as a group.

5.6 | Comparing Ms. Falconeri and Ms. Taub's approaches to collective enterprise

Ms. Falconeri and Ms. Taub both plan for students to investigate differences between air and water molecules, the next step articulated in the curriculum materials. Both involve student ideas in working with the class toward that goal. Ms. Taub exhibits an increased attention to collective enterprise compared with Ms. Falconeri. We suggest this collective work results in more opportunities for students to act as epistemic agents. It is not uncommon for a student to make a statement and for Ms. Taub to restate or rephrase the idea and ask others to evaluate those statements, a point of contrast from Ms. Falconeri's class. While still constrained by the homework question, Ms. Taub allows more opportunities for students to build knowledge together and subsequently direct more of the discussion. She has students compare their ideas both about what they figured out and how to investigate their questions. Thus, her facilitation supports more collective enterprise in the enactment in more opportunities for students to share and connect with one another.

In sum, Ms. Falconeri provides space for students to share ideas both as a whole class and in small groups, but she ultimately directs the conversation in the way she takes up students' ideas. Ms. Taub frames the conversation by asking students to think about a specific question, and then she provides opportunities for students to engage with multiple ideas related to that question. Ms. Taub's use of the public records of student ideas supports collective enterprise for the whole class. The third case in our study illustrates even more support for collective knowledge building and suggests a third variation in epistemic opportunities for students.

5.7 | Case 3: Ms. Thornhart—consensus-motivated agency

In the final episode, Ms. Thornhart is in the same place as Ms. Taub in that the class has already investigated something about temperature's influence on water particles. Ms. Thornhart

10982736, 2023, 7, Downloaded from https://onlinelibrary.wiley.com/doi/10.1002/tea.21841 by Northwestern University Libraries, Wiley Online Library on [08/11/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

makes a change to the lesson in the way she structures this opening conversation. Like Ms. Taub, Ms. Thornhart leverages technology to make student ideas public to the whole class.

At the beginning of class, Ms. Thornhart asks students to respond to a question in a Google Doc on their Chromebooks about what they figured out yesterday. This creates a visible record of responses available to all students. Next, Ms. Thornhart directs students to select and share about another student's ideas they identify as similar to how they initially responded. Like Ms. Taub's class, students immediately have opportunity for collective enterprise as they read the responses of their peers and connect them to their own thinking. Several students shared about what they figured out the day before about hot and cold water:

- "Hot water could make food coloring rise. Cold water could make food coloring fall. The video showed it to us."
- "I said hot water particles take up more space than cold water particles 'cause they're spread out."

In response, Ms. Thornhart prompts students to support multiple moments of collective enterprise with questions similar to Ms. Taub's:

- "Who also had something similar?"
- "Does that sound like what you were saying?"
- "Is there something you want to add or change?"
- "Does that help us connect these ideas?"

These questions not only encourage group sensemaking, but they also help students to continue revising their developing model of air and water molecules. Next, Ms. Thornhart summarizes the conversation and asks students to talk with partners to collectively identify areas of whole class agreement:

> *Ms. Thornhart*: Ok so, so it seems like at least from the people that I've heard from we are in agreement. Maybe somebody we have not heard from yet, what seems like the idea that we are all agreeing on here, about why the level of that water changed? Why the volume changed while it was heated? Based on what your classmates were saying. Somebody I have not heard from yet. What does that tell us? … Talk to your neighbor and this is what I want you to talk about, based on what you just heard your classmates say, what does it seem like they are agreeing on about why the volume in that capillary tube increased? Why did that water level go up when it was heated? Go ahead, close your Chromebooks so they are not a distraction, talk to your neighbors and I want to hear from someone that I have not heard from yet this morning. Go ahead.

Ms. Thornhart directs students to work together to identify what ideas have emerged as areas of agreement in the discussion so far. In doing so, she sets the stage for students to construct and reconstruct initial explanations for the behavior of water. She then asks two new students to share, thus involving more individuals in the collective work. The students indicate that they think hot water expands and takes up more space because the particles are moving faster. By this point, Ms. Thornhart has included a dozen students in conversation. Next, Ms. Thornhart makes another move to support collective enterprise through a vote.

10982736, 2023, 7, Downloaded from https://onlinelibrary.wiley.com/doi/10.1002/tea.21841 by Northwestern University Libraries, Wiley Online Library on [08/11/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Ms. Thornhart: Ok. What do you guys think? If that's making sense to you, thumbs up. If you are like, "No. That's not what I was thinking at all," thumbs down. If you are like, "I'm still super confused and not sure," give me a sideways. Everybody has to have a thumb because you are either on board, disagreeing, or unsure. I'm seeing mostly thumbs up, so I'm going to jot this down. If I'm hearing you guys correctly, most of you seem to be saying that heat causes the particles to move faster and therefore expand. But not everybody was 100% sure of that, so maybe we can do a little more investigating today. What I was thinking about today might help us with this.

The public vote gives students access to their collective thinking, similar to Ms. Taub's projected homework responses and the table discussion in Ms. Falconeri's class. A nuanced difference in Ms. Thornhart's approach is a more open-ended question for students. Ms. Taub and Ms. Falconeri facilitated conversation regarding air versus water molecules. Ms. Thornhart starts by asking students what they figured out yesterday. Then she asks students to compare responses and look for similarities. After some level of agreement is found among several students, she checks in with the class and asks students if their thinking is similar with the prevailing idea or not or if they are confused, continuing to frame the question as an open one. By asking students a general question about agreeing or not, Ms. Thornhart continues to invite all students rather than limiting to a specific idea preferred by herself or others. Rather than taking "mostly thumbs up" as consensus, Ms. Thornhart recognizes that "not everybody was 100% sure" and suggests they keep investigating the issue, setting students up to engage in the science practices of developing models, constructing explanations, and engaging in argumentation. Next, Ms. Thornhart invites epistemic agency from somebody who remains unconvinced:

Ms. Thornhart: Somebody who is not totally convinced of this, can you let us know what you are thinking so we know what we need to do to maybe get some more evidence?

Lourdes: Um. I'm not entirely sure because, just because it's hot does not mean it's taking more space. Maybe because it moves around but, I'm not definite on that. I feel like there could be some other explanation.

Ms. Thornhart: Ok that's fair. That's fair. Any other thoughts about why you are not convinced of this yet? Which is ok. We can work something out.

Carter: Um we came up with particles do not expand when they are heated. They just move faster so they take up more space.

Ms. Thornhart: Oh ok. So am I understanding? So Carter am I understanding correctly? The particles themselves aren't expanding. It's just that because they are moving around, it's taking up more space. [Carter agrees] Ok does that help clarify for some people who were not sure of this? ... Does that help address what you were thinking Lourdes?

Lourdes: It helps a bit but I'm not entirely convinced.

10982736, 2023, 7, Downloaded from https://onlinelibrary.wiley.com/doi/10.1002/tea.21841 by Northwestern University Libraries, Wiley Online Library on [08/11/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Ms. Thornhart: Ok that's fine. So let us do a little more investigating. So we did this with water yesterday, right? Is there something else that we could explore to see? Are there other types of particles that might behave the same way or differently that we might be able to look at?

Ms. Thornhart invites epistemic agency in this conversation, promising "we can work something out." As students identify what they seem to agree on and what parts they are still figuring out, Ms. Thornhart makes that uncertainty the focus of next steps, and invites students to provide ideas that could help the class further develop their thinking. When Carter shares an idea, Ms. Thornhart circles back to Lourdes to see if the new idea convinces her. Although Ms. Thornhart asks a specific question (i.e., "Are there other types of particles that might behave the same way or differently that we might be able to look at?") that aligns with her planned direction for the day, that question directly connects with the varying ideas among students. Her move here supports the pursuit of shared science knowledge. She leverages disagreement to help the class face the potential confusion and work through it. Indeed, open questions and lack of agreement are central in the storylines approach (Reiser et al., 2021) and essential for authentically engaging with science practices.

The skepticism that Lourdes expresses is connected to an important element of the particle model that is often confusing for students. The students are correct the particles do not change size and expand when the material is hotter. In fact, this could be seen as a counter argument against substances expanding when they get hot. Thus, it is worth the teacher acknowledging the concern and helping the rest of the class recognize this potential ambiguity. For the explanatory model targeted at this grade level, it is critical to understand what *does* change to allow the substance to take up more space—the population of particles takes up more space because they spread out, but the population numbers have not changed nor has the size of each member of the population.

The way Ms. Thornhart presents the vote and the follow-up conversation illustrates the ways in which this focus on collective knowledge-building supports engagement with the science practices. Ms. Thornhart solicits areas of disagreement and encourages students to share their questions or problematize the prevailing model in order for the class to continually revise their scientific model based on developing reasoning.

One last notable characteristic of this conversation is the way that Ms. Thornhart responds to students answering her question in unexpected ways.

Sonny: I had a question. Maybe we could do. Last year we took the syringes and we saw if the water is compressible.

Ms. Thornhart: Ok. See if warm water is compressible. Ok tell me why. Why might you want to do that?

Sonny: Because the particles would be more spread out so it might be able to compress.

Ms. Thornhart: Ok so that's an interesting idea that might be something we can explore. Yeah, Lourdes?

10982736, 2023, 7, Downloaded from https://onlinelibrary.wiley.com/doi/10.1002/tea.21841 by Northwestern University Libraries, Wiley Online Library on [08/11/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Lourdes: I disagree a bit with Sonny because we just wrote that it's not the particles themselves, it's the water. So would not that mean it would not compress that much? It'd be harder to compress 'cause it's more spread out. It'd already be pushing back.

Ms. Thornhart: Ok it might be something we want to explore but what I'm wondering is, and maybe, let us jot that down so we do not lose that idea. So maybe see if hot water is compressible. Um I want to back track for a second because I'm curious about is this like this for other things besides water? So we can definitely look at that, but let us think for a second. Yeah, Carla?

Carla: Um, I learned somewhere that water is like the only thing that can be like solid, liquid, and water. I mean solid, liquid, and gas. I do not know if that's right, but I think so.

Ms. Thornhart: Ok, so do you think water as a gas behaves the same way? That like the particles if water as a gas would move the same way? Meaning faster when it's heated or slower when cooled? How might we look into that when water is a gas? So I was actually doing a bit of thinking um. Before I share my thinking, go ahead.

Carla: Um, this might not work but what if we put like a bottle we could see through. We put a balloon on the top and then we put heat on the bottom. We could see like if the water, yeah. If the water is getting warm if the steam is blowing the balloon up. That might show us if it's expanding.

At this point, Ms. Thornhart makes a connection between Carla's thought and something that another student shared the day before.

Ms. Thornhart: Ok so I'm really glad you mentioned that [Carla]. I was gonna say yesterday, Milo, do you remember you made a connection to something we did last year?

Milo: Well, I'm not really sure which [experiment], but we did experiments about if air takes up space, if air has size, if air has weight.

Ms. Thornhart: Right so might we be able to do that to help us understand this idea of particles moving and does it expand? I pulled some of that stuff out again so I thought it might be worth taking a look at. I'm so glad you thought about that.

These students have been in Ms. Thornhart's class for science for 2 years. Since Ms. Thornhart's ultimate plan was to revisit and modify an experiment they did together last year, we know that when she first asks students about other molecules to consider, she was looking for a student to mention air molecules. However, the first student to respond, Sonny, suggests compressing hot water, which contradicts the request to consider molecules other than water. Rather than redirecting or passing over the comment, Ms. Thornhart entertains Sonny's idea and supports him as an epistemic agent. She asks why Sonny wants to consider hot water and Lourdes also provides her thoughts. Ms. Thornhart validates the idea as a possibility and

10982736, 2023, 7, Downloaded from https://onlinelibrary.wiley.com/doi/10.1002/tea.21841 by Northwestern University Libraries, Wiley Online Library on [08/11/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

writes it down, noting that "it might be something we want to explore." Thus, she further supports these students as epistemic agents. Although Ms. Thornhart does eventually guide students to revisit her question regarding other types of molecules, her methods of soliciting and entertaining student ideas are somewhat more expansive than in the previous two classrooms.

5.8 | Looking across cases

Similar to Ms. Taub and Ms. Falconeri, Ms. Thornhart had a predetermined direction for class in mind (as articulated in the storyline), but she organizes the opening class discussion around students determining their agreed upon science knowledge both by considering the Chromebook responses and through the class vote. Additionally, she asks students to name additional information needed for better understanding of prevailing ideas when they are unconvinced. In each of these exchanges, Ms. Thornhart uses the idea of collective knowledge building as essential to their discussion.

This conversation differs somewhat from the previous two in that Ms. Thornhart places the most emphasis on hearing and incorporating as many student ideas as possible, particularly from students who are unsure of or not convinced by the prevailing idea in the discussion. Her actions are also different from the previous two teachers in that Ms. Thornhart does very little to direct or frame the conversation beyond asking students to identify ideas they agree upon, share additional thoughts, and consider how their thoughts fit together or not. In this, she provides multiple opportunities for epistemic agency by repeatedly asking students about the kinds of evidence they need to be convinced of an idea or for details regarding why they are unsure about ideas. Because of this focus on involving all students in identifying where their community agrees and where it disagrees, we refer to this approach as *consensus-motivated agency*.

It is important to stress that by "consensus" we do *not* mean that all students accept the same conclusion and line of reasoning. Knowledge-building work in science, whether as a discipline or within classrooms, does not progress linearly from questions to final explanations, models, and theories (Erduran & Dagher, 2014; Lehrer & Schauble, 2006; National Research Council, 2012). The process of negotiation of ideas in a learning community means that periodically the classroom takes stock of where they are in knowledge building, identifying what parts of an explanation they agree on and can now take as uncontentious, or "stabilized knowledge" (Manz, 2015). At the same time, the community needs to identify gaps in understanding and areas of disagreement to figure out what they need to investigate next. In Ms. Thornhart's class, they have figured out that they agree on the idea that water expands when heated, but they are split as a class on the explanation. Some in the class argue that the particles are taking up more space because they are more spread out when the material is heated, while others are not persuaded of this explanation. Ms. Thornhart's apparent goal in this discussion is to get the class to collectively assess where they are, with all students weighing in and taking a position, and identifying points of common ground and areas of open questions or disagreement. If there is disagreement, she wants that disagreement to be surfaced, so that the class can move forward and address it. In this way, the class has reached common ground on advances, gaps, and areas that need to be resolved.

There are many similarities across these three classrooms. All three teachers work to minimize their own contributions to class discussions and to elevate student ideas as much as possible—actualizing epistemic agency by giving up their authority as the only source of knowledge in the class. Each uses a different public display of student ideas to help orient the students

10982736, 2023, 7, Downloaded from https://onlinelibrary.wiley.com/doi/10.1002/tea.21841 by Northwestern University Libraries, Wiley Online Library on [08/11/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

toward those thoughts and invite collective knowledge-building. All three ask students to build understanding collectively but vary in the extent to which members of the class community are all partners in the joint knowledge-building. We suggest that this variation in the classroom's realization of collective enterprise may influence the opportunities for student epistemic agency. We have characterized three variations, that we suggest are emergent in these cases: directed agency, framed agency, and consensus motivated agency.

In directed agency, the teacher consistently asks students to share without providing evaluative comments in order to surface multiple perspectives and thinking about science ideas. These invitations to agency may make more students feel comfortable voicing ideas because they know all ideas are welcome, regardless of "correctness." She also identifies ideas from a public display of student questions. The teacher selects which student ideas are elevated for full-class consideration both out of class discussion and from the Driving Question Board, but she always emphasizes that the focus of their conversation and activities is connected to student ideas—regularly actualizing agency for students. Collective enterprise is invited by asking students to add on or comment about these elevated ideas or discuss the ideas in small groups. Since students are only asked to consider some ideas with the full class, there are those who will not have the opportunity to work out how their thoughts interact with those of others. This is important for making sense of and incorporating various ideas into sensemaking about science, but opportunities to develop and refine models are less organic. As a result, the teacher and students work to co-construct knowledge, but the directed nature of the conversation leaves some ideas unincorporated.

In framed agency, the teacher sets the parameters for a conversation and then invites students to engage in a collective enterprise of making sense of and developing models for their understanding within those parameters. This shared work is supported through a public display of student ideas. Since all student ideas are visible, all students have the opportunity to know that their ideas are under consideration by everyone else in the classroom community (actualizing collective enterprise). Instead of selecting student ideas to elevate as was evident in directed agency, the teacher asks students what they think about the different public ideas (inviting collective enterprise) and what makes sense for next steps to further test and build their models (inviting epistemic agency). However, similar to directed agency, the collective knowledge building is limited by the initial framing of the class conversation and activities. Those students whose current science reasoning lies outside of the framed conversation do not have a natural opportunity to voice their alternate ideas.

Finally, in consensus-motivated agency, the teacher centers the whole class conversation by inviting collective enterprise and asking students to identify agreed upon understanding. When the conversation surfaces questions and disagreement, the teacher invites epistemic agency by asking students for ideas about the next steps in building their collective knowledge. Similar to framed agency, this approach includes asking students to evaluate a public and accessible display of student ideas (inviting collective enterprise). What is different in this case is that the premise of the conversation is for students to do the work of collective knowledge building rather than address a specific content-related question, as in framed agency, or respond to specific teacher questions, as in directed agency. In other words, the only limitation the teacher puts on the conversation is for students to share about their ideas (actualizing collective enterprise) to help the group identify what needs to happen next to refine their models and test their ideas (actualizing epistemic agency). This wholesale approach to collective knowledge building does not place the same limitations on who can be a part of the work as in directed or framed agency. As a result, all students have more opportunities to experience agency under

10982736, 2023, 7, Downloaded from https://onlinelibrary.wiley.com/doi/10.1002/tea.21841 by Northwestern University Libraries, Wiley Online Library on [08/11/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

TABLE 2 Case summary

	Ms. Falconeri: Directed agency	Ms. Taub: Framed agency	Ms. Thornhart: Consensus-motivated agency
Collective Enterprise	Invitations: Individual students are invited to offer ideas toward developing the class model, to add on to one another's ideas, or to indicate if they agree with one another.	Invitations: Students as a group are invited to consider their ideas for model building and planning an investigation alongside the ideas of others.	Invitations: All students are repeatedly invited to participate in public activities for expressing agreement or disagreement with one another regarding developing models.
	Actualizations: Students make individual contributions to collective knowledge-building about the developing model at teacher prompting.	Actualizations: Teacher asks multiple students to make sense of and resolve public and competing ideas regarding planning an investigation.	Actualizations: Teacher repeatedly uses identified agreement and disagreement to encourage student contributions to collective work of developing models and planning investigations.
Epistemic Agency	Invitations: Teacher often asks for student ideas and tells students their ideas matter for making sense of science ideas, but there is repeated focus on specific ideas.	Invitations: Teacher regularly asks for student ideas in planning and carrying out an investigation and tells students their ideas matter for developing explanations and models.	Invitations: Teacher constantly asks for student ideas, specifically additional investigation ideas, seeking greater student agreement.
	Actualizations: Actualization occurs for those students whose science ideas the teacher decides move the class in efficient ways toward curricular goals or those who agree but do not have their voices elevated.	Actualizations: Actualization occurs for those students who offer their ideas for the investigation to the class when invited, or those who agree but do not have their voices elevated.	Actualizations: Actualization occurs for most students as making sense of multiple student artifacts as well as constant additional student voices make up the substance of class conversation around planning an investigation and developing models.

10982736, 2023, 7, Downloaded from https://onlinelibrary.wiley.com/doi/10.1002/tea.21841 by Northwestern University Libraries, Wiley Online Library on [08/11/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

10982736, 2023, 7, Downloaded from https://onlinelibrary.wiley.com/doi/10.1002/tea.21841 by Northwestern University Libraries, Wiley Online Library on [08/11/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

consensus-motivated agency. Additionally, opportunities for students to ask questions, develop models and plan investigations open up in consensus-motivated agency in a manner that is comparatively limited in the other two classes.

Table 2 summarizes the characterization of inviting and actualizing collective enterprise and epistemic agency across each of the three cases. Moving from left to right across the table illustrates the increased attention to collective enterprise evident across the three cases. In directed agency, actualizing a collective enterprise is a discrete activity for select students that occurs within a larger class conversation. In framed agency, the actualization of a commitment to a collective enterprise extends to the full class community, but activities toward that end are still limited. However, in consensus-motivated agency, actualizing a collective enterprise is the motivation behind the full class conversation for all participants.

We suggest that these differential levels of attention to a collective enterprise directly influence the opportunities for epistemic agency in the classrooms. Moving from left to right across the bottom panel of Table 2 illustrates increased and more widespread opportunities for students to experience actualized epistemic agency. Not only do more students contribute their ideas to class conversation moving from directed to framed to consensus-motivated agency, but there are also more moments where student ideas are what motivate the discussion. In other words, moving from left to right, we see the teachers in each class giving up more of their authority to students for knowledge-building work and actualizing epistemic agency.

6 | DISCUSSION

We investigate how three teachers enacted science curricula designed around the goal of meaningfully engaging students in the science practices. We characterized variation in teacher enactments and resulting student opportunities for epistemic agency in terms of how open or structured the teachers' support for sensemaking is, and how grounded next steps are in students' own conversations about what they have figured out. While we have described these contrasts with general terms of "directed," "framed," and "consensus motivated," it is important to stress that the variation in forms identified in these cases are manifested within the context of student engagement in the disciplinary practices of science taken up in each of the respective classrooms.

As in the larger scientific community, students build scientific knowledge by collectively engaging in science practices of posing questions; planning investigations; developing and revising models; and arguing from evidence (Carrier, 2013; Erduran et al., 2018; Latour, 1987; Pickering, 2010; Rouse, 2015). Further, they enact their agency through engaging in those same practices. Teachers must structure opportunities for epistemic agency and collective knowledge building to support students' meaningful engagement in those practices. The direction and framing specifically focus on the practices in science that determine the direction and results of knowledge building and how agentive students are invited to be in that space—the practice of asking questions and identifying problems (why CCNs cannot be created simply by adding substances to air) to define direction and design of investigations (how to test the influence of temperature on air molecules) facilitate students' developing understanding along the way to continually revise scientific models. In the cases where we saw directed and framed agency, students had multiple opportunities to engage in these science practices, but the engagement in them could be somewhat limited. Consensus-motivated agency refers to the teachers' support of students figuring out what they have agreed on in terms of which aspects of the findings they can explain (why substances expand when heated) and the scientific mechanism that explains

10982736, 2023, 7, Downloaded from https://onlinelibrary.wiley.com/doi/10.1002/tea.21841 by Northwestern University Libraries, Wiley Online Library on [08/11/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

the finding (the behavior of particles of a hotter or colder substance). This evaluation of consensus is central to the practice of argumentation and working toward consensus upon identifying disagreements is an integral part of revising models and building and revising explanations (Carrier, 2013). Thus, our characterization of variations in collective enterprise and epistemic agency is intended to be seen as a consequence of classroom activities deeply contextualized within the practices of science but ultimately realized by students' own actions.

Our findings suggest how attention to a collective enterprise can provide both the motivation and opportunity for students to adopt a greater role in sensemaking by taking on more epistemic agency in the work of co-constructing models and explanations. Other emergent work focuses on the interplay of epistemic agency and the co-construction of science ideas (Chen, 2022; Chen & Techawitthayachinda, 2021). These studies particularly focus on the usefulness of epistemic uncertainty in co-constructing science ideas, while our focus is on how co-construction influences the types of epistemic opportunities for students. This developing theory regarding the interplay of epistemic agency and collective enterprise has implications for design of professional development and other teacher supports regarding some specific pedagogical shifts that may help transform classrooms into spaces where students are more likely to feel like partners with teachers in developing science knowledge as they participate in science practices (Berland et al., 2016; Chen, 2022; Chen & Techawitthayachinda, 2021; Ko & Krist, 2019; Miller et al., 2018; Stroupe, 2014).

Schools have developed a resilient system of expectations for students and teachers about their respective roles and responsibilities that is centered on teacher control of knowledge and students (McNeil, 1998). Unfortunately, these systems perpetuate a false separation between scientific understanding and scientific processes (Erduran & Dagher, 2014). Altering participant structures needs to go deeper than laying out a new set of instructions for a particular task—teachers need to cultivate and maintain *classroom norms* consistent with the target shifts in epistemic agency (Lehrer & Schauble, 2006; Manz, 2015; Yackel & Cobb, 1996). In these cases, we saw that further attention to the collective knowledge-building aspects of that work was connected to student agency. Simply taking up new instructional materials that use new tasks and discourse prompts are likely insufficient to shift students' expectations about their roles and responsibilities. Here, we see that specific moves during enactment may be consequential to the way students engage in the knowledge-building work and we begin to provide specific ideas for how to practically make these shifts. These results are consistent with other emerging literature regarding how teacher messaging about student epistemic agency influences the ways that students engage in science practices (Ke & Schwarz, 2021). Additionally, our findings reinforce the idea that the pursuit of scientific knowledge is most authentic and productive when it is a collective activity that leverages individual approaches scientific inquiry (Carrier, 2013; Longino, 1990).

We have not yet taken up the broader conditions that may help explain the variations in practice we see in these cases and that might provide directions for future work by our group and others. Certainly, we understand that teachers are making in-the-moment decisions for a wide range of reasons. While we argue that some approaches provide more authentic science learning experiences for students than others, we also acknowledge that teachers daily navigate the tension between these authentic experiences and adhering to school, district, and state standards and accountability practices; harried school schedules; and the myriad of classroom interruptions that can hamper thoughtful and deep activities such as consensus-building. However, we also suggest that careful understanding of the ways these differential approaches to supporting a collective enterprise influences student experiences are key to enabling more teachers to support opportunities for students to experience epistemic agency.

7 | CONCLUSION

In this article, we present a multiple-case study designed to uncover variation in collective enterprise and epistemic agency with the intent of elaborating a theory about what co-variation of the two constructs may mean for student experiences in classrooms. Future work that would productively build the emerging theory regarding the relationship between collective enterprise and epistemic agency would include analysis with more expanded and varied data to identify if our conjectures can be replicated. Additionally, further analysis of classroom video alongside teacher and student reflections would provide information regarding how opportunities for epistemic agency perceived in classroom video in this study are a true part of explicit teacher practice and student experiences in the classroom. Finally, we suggest that teachers' influence over classroom conversation is not the only way that they may be able to change both the collective and agentive experiences for their students. Further research is needed to carefully investigate other ways that teachers' moves can influence student experiences and the relationship between a collective enterprise and opportunities for epistemic agency in classrooms.

Enacting curriculum designed to create classroom environments that bring a group of students together to engage in collective knowledge-building work is incredibly complex. As our field struggles with how to shift classroom practice, it is essential that this effort be grounded in the deep and difficult work as it unfolds in a range of real classrooms with teachers and students and considers the important variations in enactment and their implications.

ORCID

Jessica L. Alzen https://orcid.org/0000-0002-1706-2975
William R. Penuel https://orcid.org/0000-0001-7096-6669
Brian J. Reiser https://orcid.org/0000-0002-2961-0385
Jason Y. Buell https://orcid.org/0000-0003-0219-0031

ENDNOTES

[1] Data rights owed by the International Society of the Learning Sciences and shared here with permission (c.f., https://repository.isls.org/bitstream/1/6467/1/1879-1886.pdf)

[2] All teacher and student names are pseudonyms.

[3] See the supplemental materials for a summary of the Fog storyline.

REFERENCES

Alzen, J. L., Edwards, K., Penuel, W. R., Reiser, B. J., Passmore, C., Griesemer, C. D., Zivic, A., & Murzynski, C. (2020). Exploring the connections between epistemic agency and a commitment to the collective enterprise of sensemaking in the science classroom. In I. S. Gresalfi & M. Horn (Eds.), *The interdisciplinarity of the learning sciences, 14th international conference of the learning sciences (ICLS) 2020* (Vol. 4, pp. 1879–1886). International Society of the Learning Sciences. https://doi.org/10.22318/icls2020.1879

10982736, 2023, 7, Downloaded from https://onlinelibrary.wiley.com/doi/10.1002/tea.21841 by Northwestern University Libraries, Wiley Online Library on [08/11/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Berland, L. K., Russ, R. S., & West, C. P. (2020). Supporting the scientific practices through epistemologically responsive science teaching. *Journal of Science Teacher Education*, *31*(3), 264–290. https://doi.org/10.1080/1046560X.2019.1692507

Berland, L. K., Schwarz, C. V., Krist, C., Kenyon, L., Lo, A. S., & Reiser, B. J. (2016). Epistemologies in practice: Making scientific practices meaningful for students. *Journal of Research in Science Teaching*, *53*(7), 1082–1112. https://doi.org/10.1002/tea.21257

Bielaczyc, K., & Collins, A. (1999). Learning communities in classrooms: A reconceptualization of educational practice. In C. M. Reigeluth (Ed.), *Instructional-design theories and models: A new paradigm of instructional theory* (pp. 269–292). Lawrence Erlbaum Associates.

Bowen, G. A. (2006). Grounded theory and sensitizing concepts. *International Journal of Qualitative Methods*, *5*(3), 12–23. https://doi.org/10.1177/160940690600500304

Brown, A. L., & Campione, J. C. (1990). Communities of learning and thinking, or a context by any other name. *Human Development*, *21*, 108–125.

Brown, A. L., & Campione, J. C. (1994). Guided discovery in a community of learners. In K. McGily (Ed.), *Classroom lessons: Integrating cognitive theory and classroom practice* (pp. 229–270). MIT Press.

Brown, A. L., & Campione, J. C. (1996). Psychological theory and the design of innovative learning environments: On procedures, principles, and systems. In L. Schauble & R. Glaser (Eds.), *Innovations in learning: New environments for education* (pp. 289–325). Mahway.

Carlone, H. B., Haun-Frank, J., & Webb, A. (2011). Assessing equity beyond knowledge- and skills-based outcomes: A comparative ethnography of two fourth-grade reform-based science classrooms. *Journal of Research in Science Teaching*, *48*(5), 459–485. https://doi.org/10.1002/tea.20413

Carrier, M. (2013). Values and objectivity in science: Value-ladenness, pluralism and the epistemic attitude. *Science and Education*, *22*(10), 2547–2568. https://doi.org/10.1007/s11191-012-9481-5

Cazden, C. (2001). *Classroom discourse: The language of teaching and learning* (2nd ed.). Heinemann.

Chen, Y. C. (2022). Epistemic uncertainty and the support of productive struggle during scientific modeling for knowledge co-development. *Journal of Research in Science Teaching*, *59*(3), 383–422. https://doi.org/10.1002/tea.21732

Chen, Y. C., & Techawitthayachinda, R. (2021). Developing deep learning in science classrooms: Tactics to manage epistemic uncertainty during whole-class discussion. *Journal of Research in Science Teaching*, *58*(8), 1083–1116. https://doi.org/10.1002/tea.21693

Collins, A., Brown, J. S., & Newman, S. E. (1989). Cognitive apprenticeship: Teaching the crafts of reading, writing, and mathematics. In L. B. Resnick (Ed.), *Knowing, learning, and instruction: Essays in honor of Robert Glaser* (pp. 453–494). Erlbaum.

Cresswell, J. W. (2013). *Qualitative inquiry and research design: Choosing among five approaches*. Sage Publications.

Damşa, C. I., Kirschner, P. A., Andriessen, J. E. B., Erkens, G., & Sins, P. H. M. (2010). Shared epistemic agency: An empirical study of an emergent construct. In. *Journal of the Learning Sciences*, *19*(2), 143–186. https://doi.org/10.1080/10508401003708381

Eisenhardt, K. M. (1989). Building theories from case study research. *Academy of Management Review*, *14*(4), 532–550.

Engle, R. A. (2012). The productive disciplinary engagement framework: Origins, key concepts and developments. In D. Y. Dai (Ed.), *Design research on learning and thinking in educational settings: Enhancing intellectual growth and functioning* (pp. 161–200). Routledge.

Engle, R. A., Langer-Osuna, J. M., & de Royston, M. M. (2014). Toward a model of influence in persuasive discussions: Negotiating quality, authority, privilege, and access within a student-led argument. *Journal of the Learning Sciences*, *23*(2), 245–268. https://doi.org/10.1080/10508406.2014.883979

Engle, R. A., & Conant, F. R. (2002). Guiding principles for fostering productiver disciplinary engagement: Explaining an emergent argument in a community of learners classroom. *Cognition and Instruction*, *20*(4), 399–483. https://doi.org/10.1207/S1532690XCI2004

Erduran, S., & Dagher, Z. R. (2014). Reconceptualizing the nature of science for science education. https://doi.org/10.1007/s11191-015-9800-8

Erduran, S., Kaya, E., & Dagher, Z. R. (2018). From lists in pieces to coherent wholes: Nature of science, scientific practices, and science teacher education. In J. Yeo, T. W. Teo, & K. S. Tang (Eds.), *Science education*

10982736, 2023, 7, Downloaded from https://onlinelibrary.wiley.com/doi/10.1002/tea.21841 by Northwestern University Libraries, Wiley Online Library on [08/11/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

research and practice in asia-pacific and beyond (pp. 3–24). Springer. https://doi.org/10.1007/978-981-10-5149-4_1

Flyvbjerg, B. (2006). Five misunderstandings about case-study research. *Qualitative Inquiry*, *12*(2), 219–245. https://doi.org/10.1177/1077800405284363

Ford, M. J., & Forman, E. A. (2006). Redefining disciplinary learning in classroom contexts. *Review of Research in Education*, *30*, 1–32. https://doi.org/10.3102/0091732X030001001

Ford, M. J., & Wargo, B. M. (2012). Dialogic framing of scientific content for conceptual and epistemic understanding. *Science Education*, *96*(3), 369–391. https://doi.org/10.1002/sce.20482

González-Howard, M., & McNeill, K. L. (2019). Teachers' framing of argumentation goals: Working together to develop individual versus communal understanding. *Journal of Research in Science Teaching*, *56*(6), 1–24. https://doi.org/10.1002/tea.21530

Herrenkohl, L. R., Palincsar, A. S., DeWater, L. S., & Kawasaki, K. (1999). Developing scientific communities in classrooms: A sociocognitive approach. *Journal of the Learning Sciences*, *8*(3–4), 451–493.

Kapon, S., Laherto, A., & Levrini, O. (2018). Disciplinary authenticity and personal relevance in school science. *Science Education*, *102*(5), 1077–1106. https://doi.org/10.1002/sce.21458

Kawasaki, J., & Sandoval, W. A. (2020). Examining teachers' classroom strategies to understand their goals for student learning around the science practices in the next generation science standards. *Journal of Science Teacher Education*, *31*(4), 384–400. https://doi.org/10.1080/1046560X.2019.1709726

Ke, L., & Schwarz, C. V. (2021). Supporting students' meaningful engagement in scientific modeling through epistemological messages: A case study of contrasting teaching approaches. *Journal of Research in Science Teaching*, *58*(3), 335–365. https://doi.org/10.1002/tea.21662

Ko, M. L. M., & Krist, C. (2019). Opening up curricula to redistribute epistemic agency: A framework for supporting science teaching. *Science Education*, *103*(4), 979–1010. https://doi.org/10.1002/sce.21511

Krist, C. S., & Suárez, E. A. (2018). Doing science with fidelity to persons: Instantiations of caring participation in science practices. In J. Kay & R. Luckin (Eds.), *13th International conference of the learning sciences* (Vol. 1, pp. 424–431). International Society of the Learning Sciences.

Latour, B. (1987). *Science in action: How to follow scientists and engineers through society*. Harvard University Press.

Lehrer, R., & Schauble, L. (2006). Scientific thinking and science literacy. In W. Damon, R. M. Lerner, K. A. Renninger, & I. E. Sigel (Eds.), *Handbook of child psychology* (6th ed., pp. 153–196). John Wiley and Sons.

Levrini, O., Levin, M., Fantini, P., & Tasquier, G. (2019). Orchestration of classroom discussions that foster appropriation. *Science Education*, *103*(1), 206–235. https://doi.org/10.1002/sce.21475

Longino, H. (1990). *Science as social knowledge: Values and objectivity in scientific inquiry*. Princeton University Press.

Manz, E. (2015). Representing student argumentation as functionally emergent from scientific activity. *Review of Educational Research*, *85*(4), 553–590. https://doi.org/10.3102/0034654314558490

Manz, E., Lehrer, R., & Schauble, L. (2020). Rethinking the classroom science investigation. *Journal of Research in Science Teaching*, *57*(7), 1148–1174. https://doi.org/10.1002/tea.21625

McGinn, M. K., Roth, W.-M. M., Boutonné, S., & Woszczyna, C. (1995). The transformation of individual and collective knowledge in elementary science classrooms that are organised as knowledge-building communities. *Research in Science Education*, *25*(2), 163–189. https://doi.org/10.1007/BF02356450

McNeil, L. M. (1998). *Contradictions of control: School structure and school knowledge*. Routledge.

Michaels, S., & O'Connor, C. (2012). *Talk science primer, Cambridge, MA: TERC*.

Michaels, S., & O'Connor, C. (2015). Conceptualizing talk moves as tools: Professional development approaches for academically productive discussion. In *Socializing intelligence through talk and dialogue*. American Educational Research Association.

Michaels, S., O'Connor, C., & Resnick, L. B. (2008). Deliberative discourse idealized and realized: Accountable talk in the classroom and in civic life. *Studies in Philosophy and Education*, *27*(4), 283–297. https://doi.org/10.1007/s11217-007-9071-1

Miller, E., Manz, E., Russ, R., Stroupe, D., & Berland, L. (2018). Addressing the epistemic elephant in the room: Epistemic agency and the next generation science standards. *Journal of Research in Science Teaching*, *55*(7), 1053–1075. https://doi.org/10.1002/tea.21459

10982736, 2023, 7, Downloaded from https://onlinelibrary.wiley.com/doi/10.1002/tea.21841 by Northwestern University Libraries, Wiley Online Library on [08/11/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

National Academies of Scienes Engineering and Medicine. (2018). *Science and engineering for grades 6-12: Investigation and design at the center*. National Academies Press. https://doi.org/10.17226/25216

National Research Council. (2012). *A framework for K-12 science education: Practices, crosscutting concepts and core ideas*. National Research Council.

National Research Council. (2015). *Guide to implementing the next generation science standards*. National Academies Press. https://doi.org/10.17226/18802

Next Generation Science Storylines. (2018). https://www.nextgenstorylines.org/

Osborne, J. (2014). Teaching scientific practices: Meeting the challenge of change. *Journal of Science Teacher Education*, *25*(2), 177–196. https://doi.org/10.1007/s10972-014-9384-1

Park, J., Michaels, S., Affolter, R., & O'Connor, C. (2017). Traditions, research, and practice supporting academically productive classroom discourse. In *Oxford research encyclopedia of education, Oxford University Press*. https://doi.org/10.1093/acrefore/9780190264093.013.21

Passmore, C. M., & Svoboda, J. (2012). Exploring opportunities for argumentation in modelling classrooms. *International Journal of Science Education*, *34*(10), 1535–1554. https://doi.org/10.1080/09500693.2011.577842

Penuel, W. R., & Reiser, B. J. (2018). *Designing NGSS-aligned curriculum materials*. Committee to Revise America's Lab Report, 1–51.

Penuel, W. R., & Watkins, D. A. (2019). Assessment to promote equity and epistemic justice: A use-case of a research-practice partnership in science education. *Annals of the American Academy of Political and Social Science*, *683*(1), 201–216. https://doi.org/10.1177/0002716219843249

Pickering, A. (2010). *The mangle of practice: Time, agency, and science*. University of Chicago Press.

Reiser, B. J., Novak, M., McGill, T. A. W., & Penuel, W. R. (2021). Storyline units: An instructional model to support coherence from the students' perspective. *Journal of Science Teacher Education*, *32*(7), 805–829. https://doi.org/10.1080/1046560X.2021.1884784

Rouse, J. (2015). *Articulating the world: Conceptual understanding and the scientific image*. University of Chicago Press.

Russ, R. S. (2018). Characterizing teacher attention to student thinking: A role for epistemological messages. *Journal of Research in Science Teaching*, *55*(1), 94–120. https://doi.org/10.1002/tea.21414

Sacks, H., Schegloff, E. A., & Jefferson, G. (1978). A simplest systematics for the organization of turn-taking for conversation. In *Studies in the organization of conversational interaction* (pp. 7–55). Academic Press. https://doi.org/10.1016/b978-0-12-623550-0.50008-2

Scardamalia, M., & Bereiter, C. (1991). Higher levels of agency for children in knowledge building: A challenge for the design of new knowledge media. *Journal of the Learning Sciences*, *1*(1), 37–68. https://doi.org/10.1207/s15327809jls0101_3

Spillane, J. P., Reiser, B. J., & Reimer, T. (2002). Policy implementation and cognition: Reframing and refocusing implementation research. *Review of Educational Research*, *72*(3), 387–431. https://doi.org/10.3102/00346543072003387

Stroupe, D. (2014). Examining classroom science practice communities: How teachers and students negotiate epistemic agency and learn science-as-practice. *Science Education*, *98*(3), 487–516. https://doi.org/10.1002/sce.21112

Tabak, I., & Baumgartner, E. (2004). The teacher as partner: Exploring participant structures, symmetry, and identity work in scaffolding. *Cognition and Instruction*, *22*(4), 393–429. https://doi.org/10.1207/s1532690Xci2204

Weizman, A., Shwartz, Y., & Fortus, D. (2008). The driving question board. *The Science Teacher*, *75*(8), 33.

Wilson, S. M. (2013). Professional development for science teachers. *Science*, *340*(6130), 310–313. https://doi.org/10.1126/science.1230725

Windschitl, M., & Thompson, J. (2006). Transcending simple forms of school science investigation: The impact of preservice instruction on teachers' understandings of model-based inquiry. *American Educational Research Journal*, *43*(4), 783–835.

Windschitl, M., Thompson, J., & Braaten, M. (2008). Beyond the scientific method: Model-based inquiry as a new paradigm of preference for school science investigations. *Science Education*, *92*(5), 941–967. https://doi.org/10.1002/sce.20259

Windschitl, M., Thompson, J., & Braaten, M. (2020). *Ambitious science teaching*. Harvard Education Press.

10982736, 2023, 7, Downloaded from https://onlinelibrary.wiley.com/doi/10.1002/tea.21841 by Northwestern University Libraries, Wiley Online Library on [08/11/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Yackel, E., & Cobb, P. (1996). Sociomathematical norms, argumentations and autonomy in mathematics. *Journal for Research in Mathematics Education*, *27*, 458–477.
Yin, R. K. (2017). *Case study research and applications: Design and methods* (6th ed.). Sage Publications.

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Alzen, J. L., Edwards, K., Penuel, W. R., Reiser, B. J., Passmore, C., Griesemer, C. D., Zivic, A., Murzynski, C., & Buell, J. Y. (2023). Characterizing relationships between collective enterprise and student epistemic agency in science: A comparative case study. *Journal of Research in Science Teaching*, *60*(7), 1520–1550. https://doi.org/10.1002/tea.21841

10982736, 2023, 7, Downloaded from https://onlinelibrary.wiley.com/doi/10.1002/tea.21841 by Northwestern University Libraries, Wiley Online Library on [08/11/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License