The Instructor's Role in a Model-Based Inquiry Laboratory: Characterizing Instructor Supports and Intentions in Teaching Authentic Scientific Practices

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ABSTRACT

Limited access to undergraduate research experiences for science, technology, engineering, and mathematics students has led to creation of classroom-based opportunities for students to participate in authentic science. Revising laboratory courses to engage students in the practices of science has been shown to have many benefits for students. However, the instructor's role in successful implementation of authentic-inquiry curricula requires further investigation. Previous work has demonstrated that navigating an instructional role within the open-ended format of an inquiry curriculum is challenging for instructors. Little is known about effective strategies for supporting students in authentic scientific practices. To address this challenge, we investigated instructors with prior experience teaching Authentic Inquiry through Modeling in Biology (AIM-Bio) in order to reveal strategies that are likely to help students succeed in this context. We took a unique approach that uncovered how instructors supported students and how they intended to support students in the scientific practices of modeling and experimental design. Analysis included in vivo recordings of instructor–student interactions paired with instructor interviews over the course of a semester. Findings detail the ways in which instructors flexibly responded to students through their in-the-moment actions. Additionally, the instructor intentions provided crucial explanatory power to explain the rationale behind teaching choices made.

INTRODUCTION

Increased use of authentic inquiry curricula in undergraduate education has created more opportunities for students to engage in scientific practices and grapple with scientific uncertainty (Wei and Woodin, 2011; Auchincloss *et al.*, 2014). This stands in contrast to traditional science curricula, with their more prescriptive laboratory activities (Gafney, 2005). Underlying this difference is a change in focus from the "right" answer to instead being an authentic inquiry of the unknown. In an authentic inquiry curriculum, students are invited into the process of scientific research. This may include generating their own hypotheses, designing experiments, analyzing data, and revising hypotheses to make discoveries about biological phenomena (Zion *et al.*, 2004; Harrison *et al.*, 2011; Wei and Woodin, 2011; Hester *et al.*, 2018). Inquiry-based courses and traditional laboratory courses require fundamentally different approaches to teaching and learning.

Teaching is a socially complex task, dependent on the motivations of teachers and students and on the unique context and practices within each classroom. To unpack the complexities of teaching, researchers have used a variety of classroom observation instruments to descriptively characterize instructional practices in science, technology,

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engineering, and mathematics (STEM) courses, such as the Reformed Teaching Observation Protocol (Sawada *et al.*, 2002), the Classroom Observation Protocol for Undergraduate STEM (COPUS; Smith *et al.*, 2013), the Laboratory Observation Protocol for Undergraduate STEM (Velasco *et al.*, 2016), and others. These observation instruments allow characterization of activities of instructors or students (e.g., working in groups, using clickers, asking questions) or classroom environments (e.g., climate, reflective practices, participation), so they are best suited for characterizing instruction on the instructor-centered to student-centered spectrum (Smith *et al.*, 2014; Swap and Walter, 2015). Existing observation instruments are limited, however, in that they only give information about the general learning environment. Information about the quality of characterized instructor activities, the dialogue between instructors and students, or the content being taught is often not captured (Bain *et al.*, 2020; McConnell *et al.*, 2021).

Beyond characterizing instructional practices in general, there is a need to specifically examine the instructional practices used to support students in the scientific practices that are a growing emphasis in current undergraduate curricula. We use the term "scientific practices" to refer to the processes used by scientists to do their research (Duschl, 2008). Observational studies of the activities of practicing scientists (e.g., Dunbar, 1999; Odenbaugh, 2005; Nersessian, 2009) have led to investigations of how a "science as practice" framework can be applied to student activities in the classroom (Lehrer and Schauble, 2006; Ford, 2008). The current study focuses on how instructors guide students in the scientific practice of modeling. Modeling is central to the process of science (Giere, 1988; Frigg and Hartman, 2006). Scientists use models as tools to make predictions, to interpret, and to generate explanations (Odenbaugh, 2005; Passmore *et al.*, 2009). In practice, modeling is a collective activity, as scientists use models to communicate their ideas and to elicit questions and arguments about scientific explanations (Latour, 1999; Nersessian, 2017). Ideally, model-based instruction should mirror all these aspects of scientific modeling practice. When curricula are designed with a science-as-practice framework in mind, the students' role changes. Instead of learning about canonical models that have already been established by scientists, students are expected to participate within a community to develop scientific knowledge through the process of building and revising models (Gouvea and Passmore, 2017; Manz *et al.*, 2020).

Much can be learned from research in K–12 education, which is rich with examples of teaching with a science-as-practice approach (e.g., Lehrer and Schauble, 2004; Stewart *et al.*, 2005; Manz, 2012). To productively engage students in scientific practices, instructors must navigate their own understanding of the purposes of these practices. For example, in the case of modeling as a scientific practice, instructors are often successful at helping their students to generate ideas about an observed phenomenon but may carry conflicting ideas about the classroom purpose for developing models. Rather than using models as a tool for students to develop and use scientific knowledge, instructors often use models to help students arrive at a specific canonical idea (Guy-Gaytán *et al.*, 2019). This type of teaching practice is inauthentic to the scientific practice of modeling and raises questions about the purpose of including these scientific practices in the curriculum. Similarly, inauthentic uses of the scientific practice of argumentation occur commonly from instructors again not understanding the purpose behind the use of this practice in the classroom (McNeill *et al.*, 2017). Together, these studies point to the role of the instructor in determining how students will engage in scientific practices. Specifically, they point to the importance of understanding an instructor's rationale for focusing on scientific practices.

Teaching is not guided by a simple algorithm but is intricately tied to one's reasoning for how learning occurs. Such reasoning can profoundly impact the ways instructors envision their role in the classroom and how they decide to interact with students (Pratt, 1998; Bryan, 2003). Therefore, it is important for us to reveal instructors' decisions behind their classroom actions to understand their teaching perspectives. By pairing an investigation of teachers' decisions with observation of their classroom actions, we hope to gain an accurate understanding of science-as-practice teaching in an undergraduate setting.

The primary goal of this study was to characterize the actions instructors used to support students during authentic scientific inquiries in classroom and to reveal their instructor intentions for doing so. Specifically, we aimed to uncover the "instructor supports" and "instructor intentions" centered around the scientific practices of modeling and experimental design. "Instructor supports" refer to what instructors say to students during interactions, while "instructor intentions" refer to the instructors' goals for carrying out a specific task with students. Our approach analyzed conversations instructors had as they supported students during these scientific practices. We also developed, carried out, and analyzed interviews in which instructors were asked to reflect on their instructor intentions behind these scientific practice tasks. We chose to examine instruction by experienced teachers with prior experience teaching inquiry curricula with documented positive student outcomes (Hester *et al.*, 2018). This differs from previous research investigating instructor practices, which more often focuses on difficulties instructors have implementing a curriculum that they did not design (Enyedy and Goldberg, 2004; Tal *et al.*, 2006; Roehrig *et al.*, 2007; Looi *et al.*, 2014). Our approach has been used in a few other studies (Hmelo-Silver, 2002; Khan, 2007) that highlight the benefit of investigating experienced instructors to provide foundational tools to better train new instructors.

Supporting Students' Inquiry

In inquiry instruction, an instructor's role is to facilitate the learning process for students rather than provide knowledge or answers. As a facilitator, the instructor models the appropriate behaviors of the tasks, coaches students, and fades scaffolds as students become more experienced (Hmelo-Silver, 2002, 2004). However, novice instructors are often seen being overly directive in their attempts to guide a student's agenda toward a specific model or answer when carrying out inquiry instruction (Guy-Gaytán *et al.*, 2019) and have challenges balancing the group dynamics during such open tasks (Derry *et al.*, 2001; Hmelo-Silver, 2002). Additionally, the influence of the instructors' prior experiences plays a role in impacting how instruction is carried out (Windschitl *et al.*, 2008; McNeill *et al.*, 2017). Instructors without any prior experiences in inquiry curricula or research often struggled more with implementing this new type of pedagogy, as they had no reference for how to carry out these tasks or support their students.

Previous research provides insights into how student teaching assistants (TAs) teach undergraduate students in a classroom inquiry. Duffy and Cooper (2020) investigated the relationship between TA teaching practices and TA perception of instructor expectations. Findings showed that TA actions do not always align with the expectations of laboratory directors, due to different ideas about what is expected for inquiry teaching and to differences in what the TAs personally believed is the right way to teach (Duffy and Cooper, 2020). Another study by Grinath and Southerland (2019) offers insight into the importance of the instructor in supporting students in the essential skill of sense-making during an inquiry course. They investigated the discourse moves in conversations between TAs and students, finding that, at different points, TAs' actions either supported or limited students' sense-making talk. They illustrated different ways in which TAs initiated conversations and responded to student ideas, which led to differences in the explanatory rigor that students achieved (Grinath and Southerland, 2019). Both studies illustrate the complexity of teaching inquiry for TAs, and pinpoint a major challenge—helping TAs to understand the goals behind instructional tasks. A final study looking at TA teaching actions by Goertzen *et al.* (2010) sought to understand both teaching practices and teaching beliefs. Findings demonstrated that individual TAs had different beliefs behind the same action they used with students, indicating that TAs have different underlying rationales for the same actions (Goertzen *et al.*, 2010). This highlights the importance of looking at the reasoning behind specific actions and underscores that actions alone do not represent an instructor's practice fully. Together, all these findings provide important insight into understanding the instructors' actions in an inquiry classroom. Specifically, they highlight the importance of looking more closely at the specific dialogue instructors have with students during the practices of an inquiry as well as the importance of trying to understand the "why" behind the actions observed.

Instructor Intentions and Beliefs

To fully understand instructors' actions, we need to understand what they are trying to accomplish, that is, their instructional intentions. Pratt (1998) defines intentions as "the teacher's statement of purpose, responsibility, and commitment directed towards learners, content, context, ideals, or some combination of these." We refer to "intentions" more narrowly, referring to how instructors intend to carry out a specific classroom task. When instructors begin a classroom task, they typically have explicit or implicit intentions in mind for how they plan to carry out that task with students. However, they must adapt their intentions and actions as they interact with students and learn more about their individual needs and learning progress (Schoenfeld, 2008; Hammer *et al.*, 2012; Gibson and Ross, 2016). Intentions are by necessity flexible, allowing instructors to carry out their goals in practice (Pratt, 1998). Because intentions are essential to how instructors support students in the moment, we chose to characterize classroom actions and the related instructor intentions to understand how instructors support students' engagement in scientific practices.

Previous work in science education has focused on instructor beliefs rather than intentions (Ravitz *et al.*, 2000; Stuart and Thurlow, 2000; Harwood *et al.*, 2006; Ferrare, 2019; Männikkö and Husu, 2019). Instructor beliefs are the most abstract component of one's teaching perspective but represent crucial underlying values of that instructor. They are held with varying degrees of confidence; some are vague and tentative, while others are central and dominant to the way a person thinks (Pratt, 1998). Studies investigating beliefs have provided new insight into the teaching perspective of instructors, including personal practical theories, teaching orientation, teaching philosophy, and teaching approach (Ravitz *et al.*, 2000; Männikkö and Husu, 2019). Instructor beliefs about teaching and learning practices provide important insight into the why behind instructional practice actions, ultimately determining whether certain actions or intentions are reasonable (Pratt, 1998). Though beliefs underlie what teachers choose to do in the classroom, it can be difficult to discern how a particular belief will translate into what a teacher chooses to do. This is due to the more abstract nature of beliefs. By contrast, intentions reveal an instructor's stated rationale behind specific classroom actions.

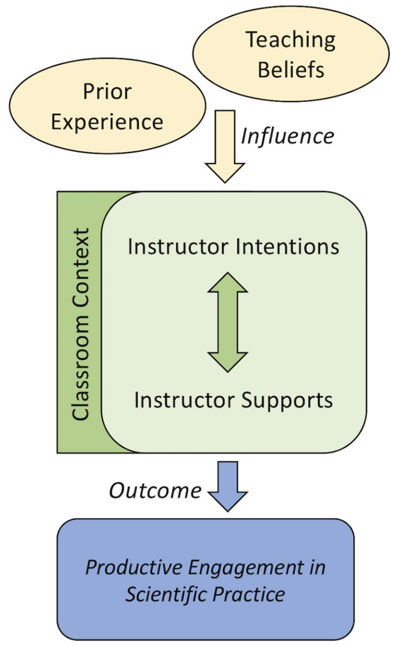

FIGURE 1. Conceptual framework of instructor reasoning. This diagram illustrates the relationships between instructor's intentions, actions, and influencing factors. The yellow circles indicates possible factors an instructor may bring to the instructional context. The green box depicts an instructor's intentions and interactions in the classroom. Finally, the blue box depicts the impact of these factors on outcomes for students.

Figure 1 illustrates our conceptual framework of instructor reasoning. When instructors are in the classroom with students (middle, green box), they are guided by their instructor intentions as they interact with students. However, even though an instructor may have clear intentions, these intentions can still be influenced by the needs of individual students, leading to an instructor adapting the supports used with students (Schoenfeld, 2008; Hammer *et al.*, 2012; Gibson and Ross, 2016). Thus, we represent the relationship between intentions and interactions as a two-way arrow. The instructor's intentions and interactions are influenced and constrained by the specifics of the classroom context (e.g., the student population, the local educational culture, and the curriculum). The instructor's intentions are made and influenced by different factors (top, yellow circles). These include an individual's prior experience as an instructor, student, or researcher and currents beliefs about teaching and learning (Pratt, 1998; Windschitl *et al.*, 2008; McNeill *et al.*, 2017). These factors play an important role as instructors develop and carry out their instructional intentions. Finally, our framework points out that an instructors' reasoning and interactions with students are key influencers of the desired student outcome in this study: productive student engagement in scientific practice (bottom, blue box).

Model-Based Inquiry Curricula

As a mode of instruction, model-based inquiry focuses on engaging students in cycles of creating, testing, and revising models (Passmore *et al.*, 2009). Scientific inquiry courses ask students to actively participate in science by constructing explanations about the natural world through the implementation of scientific practices (Ford, 2008; Passmore *et al.*, 2009). Scientists commonly engage in modeling as a scientific practice to develop evidence-based explanations of natural phenomena (Dunbar, 1999; Nersessian, 1999). Extensive research has been done that highlights the powerful sense-making students can do when engaged in model-based reasoning (Passmore and Stewart 2002; Lehrer and Schauble, 2005; Schwarz *et al.*, 2009; Louca and Zacharia, 2015). The process of modeling incorporates a variety of practices integral to the core work of science, such as hypothesizing, focusing on explanations, testing ideas through experimentation, and revising explanations in light of evidence (Windschitl *et al.*, 2008). In this study, we focus on modeling as the sense-making work of developing and revising explanatory models in response to evidence from experimental data (Passmore *et al.*, 2014).

The current study takes place in the context of Authentic Inquiry through Modeling in Biology (AIM-Bio), an undergraduate model-based inquiry introductory biology laboratory course focused on molecular and cellular biology. AIM-Bio provides opportunities for students to investigate unknown biological phenomena through authentic scientific practices. The outcomes of their investigations are unknown to the students, creating need for the students to collaborate with their peers and seek help from the instructor as a mentor. Many positive student outcomes were found to result from participation in AIM-Bio: greater sense of project ownership, increased science identity, enhanced skills for doing science, and increased understanding of the nature of science (Hester *et al.*, 2018). We would like to understand how AIM-Bio instructors support their students in the authentic science practices, specifically, investigating both the actions and intentions of these instructors that led to the positive student outcomes seen.

RESEARCH QUESTIONS

The focus of our study is to understand teaching decisions that are involved in implementing an authentic inquiry-based curriculum. Our review of the literature suggests that further work is needed to investigate how instructors support and intend to support students in scientific practices. Our study is novel, in that subjects were designers of the curriculum with prior experience as research mentors, active-learning undergraduate instructors, and instructors of the AIM-Bio curriculum. Because this population had previously demonstrated positive student outcomes in an inquiry setting (Hester *et al.*, 2018), we hypothesized that our investigation would provide unique insight into how one could productively support students in a model-based inquiry. To understand the methodology of these instructors we adopted a grounded-theory approach asking the following research questions:

1. What are the instructor's intentions for guiding students in scientific practices?
2. What supports do instructors use to guide students in scientific practices?

METHODS

Instructional Context and Study Participants

The study context is the implementation of the AIM-Bio curriculum at a university in southwest of the United States. The AIM-Bio curriculum is an introductory biology lab in molecular and cellular biology. The average class size is 24 students in each laboratory section. The students work in permanent groups of three students for the whole semester, with eight total groups in each laboratory section. The AIM-Bio curriculum (Hester *et al.*, 2018) engages students in authentic scientific practices by having them participate in a "modeling cycle" over a multiweek unit (Figure 2). In this cycle, a phenomenon of interest is explored in the first week, leading to the creation of a model to mechanistically explain the phenomenon. In the next week, students design experiments to address hypotheses and ideas in their models. The evidence from these experiments is then used to revise the mechanisms present in the original model. For analysis, we focused on the instructors' actions in a subset of the tasks: model creation, experimental design, and model revision, shown in dark blue in Figure 2. We expected these tasks to be challenging for the students and, therefore, likely to evoke guidance from the instructors. Four units were chosen for analysis: "Bacteria Growth," "Computational Cancer," "*Chlamydomonas reinhardtii* Phototaxis," and "Pathway Thinking in Yeast" (Hester *et al.*, 2018). Each unit takes about 2–3 weeks to complete and occurs in the order listed. Participant instructors were the designers of the AIM-Bio curriculum (n = 2). Data were collected according to protocols approved by the institutional review board (IRB) at our institution. Participant instructors and quoted students consented to being audio-recorded for research purposes. One of the study participants was also an author for this paper (M.S.B.). To ensure that this dual role did not compromise the validity of the study findings, M.S.B. did not participate in the analysis of instructor intentions (RQ1). M.S.B. did work with the first author (A.C.C.) to analyze instructor audio recordings, but a third coder (J.B.O.) was recruited to independently check and validate these coding results.

Data Collection

Data consisted of instructor intention interviews and in-class audio recordings of instructors. Instruction intention interviews were designed as a two-part protocol, aiming to capture the instructor intentions behind the scientific practice tasks. Analysis of these interviews focused on the first part of the interview for this study, in which the instructors were asked to reflect on their general intentions for a specific part of the modeling cycle

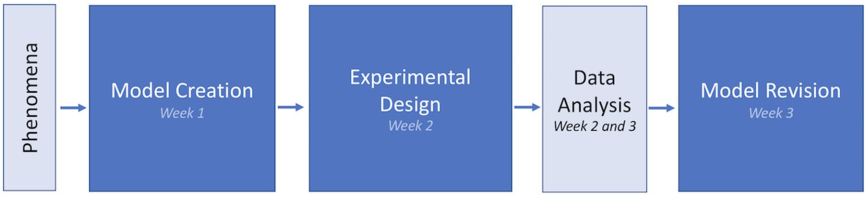

FIGURE 2. Model cycle used in AIM-Bio curriculum. Each unit has students move through a modeling cycle, simplified into three main tasks for this study: model creation, experimental design, and model revision (dark blue squares).

(i.e., model creation, experimental design, model revision) in the unit recently completed. Interviews were conducted in Fall 2018. The full interview protocol is included in Supplemental Table 1. Each instructor was interviewed at four points in the semester, within 2 weeks of the end of each relevant unit.

In-class audio was collected from instructors throughout the Fall 2017 and 2018 semesters. Instructors wore microphones attached to an audio recorder during all laboratory sections taught in the semester of interest. The recordings captured audio of both the instructors and students during conversations. However, only student audio from consenting individuals was analyzed.

Data Analysis

To address research questions 1 and 2, we used aspects of a grounded theory approach (Charmaz, 2014). Analysis for each question was conducted separately. Though significant prior work has suggested some important aspects of inquiry teaching, the specific aspects of teaching that we wished to understand (i.e., the ways in which instructors support students in scientific practices through dialogue and their rationale behind instructional supports) have not been described in sufficient detail. Therefore, we sought to base our analysis in observations and to allow coding categories to emerge from the empirical data that we collected (in-class recordings of instructors and interviews of instructors). Thus, our approach relied on inductive analysis through coding and comparing, characteristics of a grounded theory approach (Sbaraini *et al.*, 2011; Charmaz, 2014). Although qualitative coding categories emerged from data, our noticing and thinking about empirical observations were guided by the view of inquiry instruction and scientific practices that we outlined in our literature review. As called for in a grounded theory approach, our coding process, detailed later, relied upon the assumption that initial categories were provisional and were then refined through cycles of noticing and revision (Charmaz, 2014). Additionally, our approach included "theoretical sampling" (Sbaraini *et al.*, 2011; Charmaz, 2014) to explicate categories and fill in gaps in our knowledge. Specifically, analysis of in-class audio pointed to holes in our knowledge of instructor rationale, which led to the collection of further data through instructor intention interviews. Unlike a traditional grounded theory approach, our study has not yet produced a substantive theory. However, we believe that the results presented in this study move toward the future production of a theory on how to support students in model-based inquiry instruction.

Instructor Intention Interviews

To address research question 1, A.C.C. and K.M.S. conducted a qualitative coding analysis to characterize instructor intentions. Data included transcripts of four interviews in which instructors reflected on the following units: "Bacteria Growth," "Computational Cancer," "*Chlamydomonas reinhardtii* Phototaxis," and "Pathway Thinking in Yeast." A.C.C. and K.M.S. read and noticed emergent themes from a subset of this data; A.C.C. consulted the literature (referenced in our *Introduction*) to refine themes. A.C.C., K.M.S., and M.S.B. then met to discuss the themes and agree upon the coding guide, which included five major themes, each with their own different subthemes (Supplemental Table 2). The intention themes in the coding guide mainly focus on how the instructor intends to support students in the scientific practices of modeling and experimental design. For example, the instructors commonly talked about their intention to make sure the students designed an experiment that aligned with their model (*Check Alignment of Model and Data*) or their intention to create an environment where students felt comfortable sharing ideas (*Build a Supportive Classroom Culture*). The intention to *Build a Supportive Classroom Culture* also included several general teaching intentions, such as time management or wanting to promote student agency. The coding guide was then applied to the four interviews in which the instructor answered the interview questions, "What are your general goals or intentions for students during the [model-creation, experimental design, and model-revision task]?" This resulted in a total of 17 question responses across the modeling and experimental design tasks (model creation = 4, experimental design = 8, model revision = 5). Percent agreement was calculated by including codes that both researchers agreed were present. This did not include codes that both coders agreed were not present in order to set a higher threshold for agreement. Coding analysis was carried out by two independent coders (A.C.C. and K.M.S.) with 85% agreement. Additionally, Cohen's kappa was also calculated to check for chance agreement between the coders. The Cohen's kappa calculation included codes that the researchers agreed were present as well as the codes they both agreed were not present, as is standard practice. Cohen's kappa was calculated to be $\kappa = 0.86$, indicating almost perfect agreement (Cohen, 1960; Landis and Koch, 1977).

In-Class Audio

To address research question 2, A.C.C. and M.S.B. conducted a separate qualitative coding analysis to characterize the instructor supports used to guide students in the three model-cycle tasks. Transcripts of instructor audio recordings from three separate instructional units in Fall 2017 were used to develop a qualitative coding guide to describe the supports instructors provided to students during the modeling cycle. Analysis began with open reading of instructor–student group interactions in the transcripts from the different modeling cycle tasks. A.C.C. and M.S.B. read and discussed what they noticed, with specific focus on the model cycle–specific instructor supports. The emergent themes were then organized into task-specific supports from which three coding schemes were developed, one for each model-cycle task (Supplemental Tables 4–6). The unit of analysis was an episode of interaction between the instructor and a group of students. An episode began when an instructor started talking to a group of students and ended when the instructor left the group. The development and refinement of the coding scheme, using the Fall 2017 transcripts, allowed us to reach "saturation" when we were no longer seeing additional themes at the end of our analysis. This data set was also used to refine the coding guides and for the researchers to practice applying the coding guides.

For an episode to be included in the analysis, both coders had to agree upon the nature of the student activity during that task; this was done by identifying the "scientific practice" occurring in the episode (Supplemental Table 3). For example, in the model-creation episodes, students needed to be doing the model-creation task; for experimental design episodes, students needed to be hypothesizing/predicting and/or actively designing experiments; and for model revision, episodes had to include the revision of the models.

Our initial analysis did not suggest variation in coded behaviors between different instructional units. Thus, we took a sampling approach as we applied our coding scheme to instruction in Fall 2018. Two units from instruction, "Bacteria Growth" and "*Chlamydomonas reinhardtii* Phototaxis," were chosen for the analysis presented. These two units were selected because they include all three parts of the modeling cycle and provide insight into instruction at different time points of the semester. This resulted in 131 episodes (model creation = 34, experimental design = 64, model revision = 33) being included in analysis. To capture what happened in each interaction, each episode could receive multiple instructional codes. Of the 131 episodes analyzed, 76% ($n = 96$ episodes) were coded as having at least one instructional support. It is important to note, however, that our intention was to characterize the unique instructional supports that might be needed in a model-based inquiry, so our coding did not include many common actions that instructors were doing to support students. For example, we did not code instructors listening to and revoicing students' ideas or goal-posting to remind students of the relevant task. Instead, the coding guides focused on the instructor supports specific to the scientific practices of modeling and experimental design. For example, supports that pushed students to explain their model (Focus on Explanations) or help students think through controls (Support Thinking about Controls) are examples of the types of supports included. Percent agreement was calculated as it was for the coding used in the intention interviews. The calculation included codes that both researchers agreed were present and did not include codes that both coders agreed were not present to set a higher threshold for agreement. Two independent coders (A.C.C. and M.S.B.) applied the coding scheme with interrater reliability of 70%. Episode disagreements were discussed by both coders until consensus was reached. Additionally, Cohen's kappa was calculated to correct for chance occurrences of agreement between the coders. The Cohen's kappa calculation included codes that the researchers agreed were present as well as the codes they both agreed were not present, as is standard practice. Cohen's kappa was calculated to be $\kappa = 0.80$, indicating substantial agreement (Cohen, 1960; Landis and Koch, 1977).

A third coder (J.B.O.) was recruited to assure validity of the developed codes. J.B.O. was trained by A.C.C. to use the coding guide, using a combination of the Fall 2017 and Fall 2018 data. J.B.O. then applied the coding guide to one-quarter of the data from Fall 2018. Interrater agreement and Cohen's kappa were calculated by comparing J.B.O.'s coding to the consensus coding of the original researchers (A.C.C. and M.S.B.). We decided to use Cohen's kappa, which is appropriate for two coders, instead of Fleiss's kappa, which is appropriate for three coders. This was because we considered J.B.O. to be the first coder and the consensus of the original coding (by A.C.C. and M.S.B.) to be the second coder. The final interrater reliability of coding among all three researchers reached an acceptable level, 70% agreement, calculated as outlined earlier. Additionally, the Cohen's kappa was found to be $\kappa = 0.78$, indicating a substantial agreement, (Cohen, 1960; Landis and Koch, 1977). Cohen's kappa was calculated the same as outlined earlier by including codes that the researchers agreed were present and not present being included. The rate of agreement between J.B.O. and the consensus of the other coders was lower for the experimental design task relative to the other tasks. Therefore, the three coders met together to discuss disagreements on coding of episodes in the experimental design task. Results presented in this manuscript for research question 2 represent the final agreement of all three coders.

Case-Based Analysis

To demonstrate potential connections across our research questions, we conducted additional analyses of our in-class audio transcripts and instructor intention interviews. From the coding results, we picked a representative day, of one unit and one instructor, from both a modeling task and an experimental design task. These cases were then turned into timelines of instructor–student group interaction. The timelines include the time the instructor spent with each group, which groups were visited, when the groups were visited, and the different support codes that were characterized in each individual episode. As we wanted to connect the instructor supports to the instructor intentions, we also analyzed the interview response of the specific instructor for the unit of instruction shown in the timeline.

RESULTS

Research Question 1: What are the instructor's intentions for guiding students in scientific practices?

To address our first research question, we conducted interviews with the two research subjects as they taught the course. The interviews asked instructors to recall their intentions for three model-cycle tasks: model creation, experimental design, and model revision. We conducted interviews at the conclusion of four different units, providing a total of 17 different responses to be included in analysis. Qualitative coding analysis of instructor transcripts revealed five emergent themes: 1) *Check Alignment of Model and Data*, 2) *Encourage Modeling as a Cognitive Tool*, 3) *Build a Supportive Classroom Culture*, 4) *Navigate Practices of Experimental Design*, and 5) *Support Productive Efforts*. Each theme was present in all the model-cycle tasks, expect *Navigate Practices of Experimental Design*, which was specific to only that task. We elaborate on these themes by presenting how the most frequent ones were used within each of the three model-cycle tasks in the sections that follow.

Main Goal behind Model Creation: A Model Is an Explanation. The first model-cycle task, model creation, occurs at the beginning of the unit after the students observe the biological phenomena. Creating models requires the students to draw from their prior knowledge to generate an explanation for the observed phenomena. Due to the challenging nature of the task, the instructors work to support students with the sense-making aspects of model generation, as well as to help students feel comfortable enough to participate in the task. We will highlight two instructor intentions, *Encourage Modeling as a Cognitive Tool* and *Build a Supportive Classroom Culture*, to demonstrate the instructors' main goal of helping students draw models that illustrate the students' own explanations of the biological phenomena.

Interview analysis showed that both instructors' overall goal for this task was that students should create explanatory models. The instructors helped students balance the different aspects of creating models, such as understanding the biological concepts or understanding what a mechanistic explanation should include. As one instructor described her intentions for this task:

> Okay so I think overall goals would be that students understand that their model needs to be explanatory, that they understand the phenomena enough to explain some part of it, that they actually have some visualizations in there that are explanatory.—Instructor 2

In this first example, we can see that the instructor emphasized the importance of students drawing a model of their explanations. This example illustrated an instructor intention theme, *Encourage Modeling as a Cognitive Tool*. This intention often focused on the instructor trying to move students away from drawing a general picture illustrating the phenomenon and instead encouraging students to instead think mechanistically about how the phenomenon was occurring.

To further support the major goal of students building explanatory models, the instructors intended to create an environment where students felt comfortable enough to participate. In the analysis, the instructors recognized how generating ideas about a biological phenomenon could be intimidating for the students. This idea was highlighted in one instructor's response:

> [My intention is] making sure that [the students] understand that they should just feel comfortable to put ideas out there.—Instructor 2

Another response noted how encouraging and validating student ideas was important for creating this supportive environment:

> I want them to actually feel like they—to help them to kind of realize and help them feel like they do have ideas for how [the phenomenon] works.—Instructor 1

In both responses, the instructors articulated their intention of helping the students be willing to participate in the task. The instructors wanted to create a low-pressure environment where students would feel comfortable, creative, and willing to share their ideas. Both responses highlight the instructor intention theme of *Build a Supportive Classroom Culture.*

Main Goal behind Experimental Design: Alignment of Test and Question. The second model-cycle task, experimental design, occurs in the middle of the unit, after the students have already created their models and have been introduced to the available experimental tools they can use to test their hypotheses. Designing productive experiments requires students to navigate between the physical and theoretical aspects of the experiments. Findings from this analysis demonstrate that the main instructor goal for the experimental design task is that students design an experiment that will answer a question from their models. Two instructor intentions, *Check Alignment of Model* and *Data* and *Navigate Practices of Experimental Design*, will be highlighted from the instructors' responses.

From the intention interviews, a major goal that the instructors had was to support their students in aligning their proposed experiment with their experimental question. For instance, one instructor explained that:

> [I wanted to] make sure that even within an individual group, that it does not have to be a perfect experiment, but it should be an experiment that they can relate to their hypothesis and that they can actually say something about the plausibility of their hypothesis with the data they [would] get.—Instructor 1

In this example, we see the instructor intended to *Check Alignment of Model and Data*. Specifically, this instructor sought to ensure that students aligned their proposed tests with their hypotheses by helping the students remember their models from the prior task and pushing them to consider how the two tasks worked together. This often included the instructor's pushing students to think about *how* the tool they picked would allow them to gain further insight into their question.

Another instructor intention in this task was to help students *Navigate Practices of Experimental Design*. This theme focused on helping students design effective experiments. One way this was done was by asking students to think forward to expected experimental results. This often included asking students to reason about expected outcomes and make predictions. This was highlighted in one instructor's response:

> A big part of the decision they have to make is what they are actually going to see come out the other end, to help students think about how they are going to interpret the data they get and kind of help them or even just assess what they are doing in terms of, what are you going to look at at the other end? And does that make sense in terms of your goals of, like, killing the tumor and preventing metastasis?—Instructor 2

In this response, the instructor wanted to help her students to reason forward to how they would be able to use the data they would get from the experiment. The instructor wanted to support the students in first thinking about what they predicted they would see if they conducted the planned experiment. After they had an idea of what data they would get, the instructor then wanted them think about how they would interpret the data. This intention emphasized the importance of students connecting their future results back to the main goal of the activity, which was to explain the biological phenomenon.

Main Goal behind Revising Models: Incorporate Evidence into Explanation. In the final model-cycle task, model revision, the students revise their models in light of their own experimental results, as well as results from their peers. Similar to the model-creation task, revising models is a cognitively challenging task that pushes the students to think mechanistically about their explanations. However, unlike the first task, the students now have their own experimental results and findings from other students' experiments to help them make sense of the phenomenon. We will highlight how the *Encourage Modeling as a Cognitive Tool* and *Check Alignment of Model and Data* intentions play out differently in this new task compared with the earlier tasks by illustrating how they support the main instructor goal of helping students draw explanatory models using experimental evidence. One instructor described this in the following way:

> So, this is, yeah … similar to the initial model drawing actually, so one [intention] is to try to include mechanisms to the extent possible so things doing things. And also, to try to be explicit with their ideas so again, if they have an idea to try in some way to convey it through the model. And then, I mean, they just finished a day full of collecting results, so I actually want to encourage them to draw on the different pieces of data that were available.—Instructor 1

In this example, we can see that the instructor first compared this task to the model-creation task, because both focused on the students drawing models that included their own explanations of the phenomenon. The first part of her response demonstrated how the instructor wanted her students to have a mechanistic explanation. This response highlights the instructor intention theme, *Encourage Modeling as a Cognitive Tool*. The end of this instructor's response focuses on the *Check Alignment of Model and Data* intention by encouraging students to incorporate evidence into their models. We can see that the instructor wanted the students to understand how the different results can contribute to their models and how this would help with the ultimate goal of drawing a more mechanistic explanation. Another instructor's response further illustrated these ideas:

> The final model is like … you should be generative, you should explain the phenomena, and you should incorporate evidence in your thinking about this.—Instructor 2

From both of these responses, we can see that the instructor placed greater emphasis on pushing students to have more mechanistic explanations. The instructors wanted the students to be able to think through the different data and results and try to synthesize these different pieces.

Goal across All Modeling Tasks: Focusing on Mentoring Idea Development. The fifth instructor intention, *Support Productive Efforts*, has not been discussed in the context of the three model-cycle tasks. This intention occurred in all three of the model-cycle tasks explored earlier, but at a lower occurrence. The *Support Productive Efforts* intention can often be seen through the instructor highlighting productive ideas, redirecting unproductive ideas, or encouraging model and test diversity. One example of how this intention appeared during the experimental design task was:

> A classroom-wide goal [that] is kind of big in this particular activity, is to have students pursuing a diversity of ideas and generating a diversity of data, so it's a goal to, like, not over-manage with the groups to, but if possible, to maybe lean on them a little bit but to steer them in diverse directions, at least 'cause the goal is with the data in the room, they don't have to come up with the answer but that there is going to be enough there that students can work with and actually generate explanations that make sense.' Cause that, to put as almost a negative goal, to avoid the situation where the groups have all disproven their hypotheses, but they don't have actually anywhere to go from there.—Instructor 1

In this response, the instructor emphasized her goal of having a diversity of data available in the classroom. She planned to promote data diversity by giving different types of guidance to her students. This example demonstrates the instructor's strategy of tailoring the types of supports she gave to the different groups of students, in part to encourage the creation of a diversity of data for the class to consider.

Looking at the five intentions in the context of each model-cycle task allowed us to better understand the instructor intentions for each task and how these intentions differed for each task. We also wanted to get a better understanding of how often these intentions occurred over the course of the semester. We performed coding analysis of all instructor interviews to identify when each of the five intentions was discussed by each instructor. This allowed us to learn how common each intention was for each model task, as well as across the tasks. We present the results of this analysis with the total frequency of the five intentions across all three tasks in Table 1. Findings from this analysis show *Check Alignment of Model and Data* as the most common theme to occur across all three tasks, followed closely by *Encourage Modeling as a Cognitive Tool*. From the analysis presented earlier in this section, we know that all of the intention themes are working to support the main instructor goal across all three modeling tasks of getting students to draw explanatory models of their own ideas.

Research Question 2: What supports do instructors use to guide students in scientific practices?

To address our second research question, we analyzed audio-recorded episodes of instructor–student interactions (n = 131). Qualitative coding analysis revealed 18 instructor supports that varied across the three different modeling tasks. The emergent categories for the instructor intentions described in the previous section generally aligned with the categories we uncovered for supports. For example, the intention *Encourage Modeling as a Cognitive Tool*, appeared to be carried out by the instructors pushing students to include mechanistic explanations (Focus on Explanations), encouraging drawing their ideas in their model (Push to Visualize), and helping students think about their model as a sense-making and communication tool (Model as a Thinking or Communication Tool). In this section, we present the instructor supports and case vignettes within the scientific practices of modeling and experimental design. The instructor supports are organized by their alignment with the five intention themes described in the previous section (Table 1). We

TABLE 1. Instructor intention themes

Instructor intention themes[a]	Description
Check Alignment of Model and Data (11/17)	Instructors help students to connect across modeling cycle tasks. For example, instructors focus on aligning proposed experimental designs with hypotheses from their created models.
Encourage Modeling as a Cognitive Tool (10/17)	Instructors want the students to use their models to make sense of their ideas in order to create an explanation. This often focuses on the instructors pushing students to include mechanisms and systems thinking.
Build a Supportive Classroom Culture (8/17)	The instructors want to create a supportive classroom where students feel comfortable and have their ideas validated. This includes encouraging students to generate and test their own ideas and work collaboratively within and across groups.
Navigate Practices of Experimental Design (7/8*)	Instructors wants to provide guidance as students design experiments. This often includes explaining tools available, helping to think about controls, and challenging students to reason forward to expected experimental outcomes.
Support Productive Efforts (6/17)	The instructors have the goal of helping the class move toward well-supported models. Supports include encouraging diversity of ideas and directing students away from unproductive ideas.

[a]In parentheses, the first number indicates the number of episodes the code occurred in out of the possible total episodes that it could have been coded in across the three model-cycle tasks (n = 17). An asterisk (*) indicates that theme that was only coded during the experimental design tasks (n = 8).

present some of the most common supports as well as supports that were unique to the particular tasks. Specifically, we examined two classroom tasks: modeling and experimental design. Finally, we present case vignettes that highlight the connection between the instructor intentions and instructor support actions for each task.

Instructor Supports in Creating and Revising Models. From our analysis of the instructor intentions, we noted that the instructors' main goal in the model-creation task was to encourage students to draw models that illustrated their own explanations of the biological phenomena. Similarly, the instructors' main goal in the model-revision task was to encourage their students to, again, draw explanatory models, but with an emphasis on using experimental evidence to inform their explanations. As the instructors sought to *Encourage Modeling as a Cognitive Tool*, we found that they helped students propose explanations and visualize their ideas using models in both tasks. Instructors often spent time helping students explain and hypothesize mechanisms (Focus on Explanations) by encouraging students to generate ideas and pushing them to fully explain their ideas mechanistically. When we examined what instructors said during class, we saw that they encouraged students to explain their ideas as a way to invite them to participate in the task of explaining:

> So I want to you explain not just that it moves to the light but how you think that happens. What might be involved? What processes? What molecules? What mechanisms?—Instructor 2

From this example, we can see that the support Focus on Explanations is carried out by encouraging the students to come up with ideas and think more "molecularly" about their idea. In the model-revision task in particular, instructors more commonly used this support to emphasize thinking mechanistically rather than just having an explanation. For example:

> So, it is making some protein. And what do you think E does with the protein? What does the protein do?—Instructor 2

In this example, we see the instructor challenging the students to think through different aspects of their final models by trying to explain the "how" and "why."

Another aspect of helping students draw mechanistic models that appeared in the model-revision task was the instructor intention *Check Alignment of Model and Data*. Specifically, the instructors worked to help students think through how their own experimental results connected to their proposed hypotheses (Connect Evidence to Model). An example of this is:

> So how does your model explain these results? That when you take the acid out it still doesn't grow?—Instructor 1

From this example, we can see that the instructor wanted to hold the students accountable for understanding the results that they have collected. The instructor was challenging the students to make sense of their results and to think more deeply about the role those data could play in their final models. As illustrated in this example, instructors often carried out this support by assessing the alignment of a model with a group's data or data from the class.

Along with helping the students construct explanations, the instructors intended to *Build a Supportive Classroom Culture* in which students felt comfortable participating in the task and collaborating with other groups to share results. From the instructor–student interactions in model creation, we noticed the instructors commonly encouraging student tentative ideas (Encourage Emerging Ideas). One way that the instructors encouraged student ideas was by helping to distinguish the different productive ideas when multiple ideas were proposed within a group of students. For example:

> Okay, so you just said three ideas, right? So, one is they are physically interacting, one is that bacteria need certain things to grow … you are on the right track in terms of they need something to grow.—Instructor 2

Another way that the instructors encouraged student tentative ideas was by letting them know that it is okay for their models or ideas to be incorrect. For example:

> So there is not one right answer; we just want you to figure out what is AN explanation that you can draw in your model for why this is happening, why we saw all of these things, okay?—Instructor 2

TABLE 2. Instructor supports and occurrence in the modeling tasks[a]

Modeling instructor supports		Model creation percent occurrence (n = 34)	Model revision percent occurrence (n = 33)
Instructor intention: *Check Alignment of Model and Data*		24%	40%
In-class supports	**Highlighting Hypotheses** Instructor highlights potential current hypotheses within student model that would be testable.	24%	NA
	Connect Evidence to Model Support students in connecting their own data or peers' data to their model. Often includes helping students to reason through their data with the purpose of revising their current model.	NA	33%
	Check Back to Prior Model or Hypothesis Instructor brings student attention back to the students' original model or hypothesis.	NA	15%
Instructor intention: *Encourage Modeling as a Cognitive Tool*		68%	45%
In-class supports	**Focus on Explanations** Push students to fully explain ideas, often by asking follow-up questions to clarify ideas.	62%	42%
	Push to Visualize Encourage students to visually represent their thinking a model explanation.	26%	12%
	Model as Thinking or Communication Tool Instructor explicitly directs students to use their model as a way to make sense of their ideas or help others to make sense of those ideas.	12%	NA
Instructor intention: *Build a Supportive Classroom Culture*		32%	48%
In-class supports	**Make Ideas in Room Accessible** Encourage students to share their ideas with other groups and inquire about findings from others.	39%	39%
	Encourage Emerging Ideas Encourage student idea formation. Often includes encouraging initial formation of ideas, affirming acceptability of uncertainty, and emphasizing student productive ideas.	35%	21%
	Multiple Plausible Ideas Remind students that there are multiple answers, many options, and the general openness of the questions.	15%	6%
Instructor intention: *Navigate Practices of Experimental Design*		NA	3%
In-class supports	**Reasoning about Alternative Experimental Outcomes** Support students in reasoning about alternative experimental outcomes or explanations about their results.	NA	3%
Instructor intention: *Support Productive Efforts*		12%	NA
In-class supports	**Plausibility Filter** Assess student ideas and redirect ideas that are unproductive.	12%	NA

[a]Instructor supports are organized within the instructor intention themes previously characterized. Percent occurrence identifies how many episodes the support was coded in out of the total possible episodes for the model-creation task (n = 34) and model-revision task (n = 33). Not all supports were coded for in each of the tasks (indicated with NA).

From both examples, we can see that this support was used by the instructors to encourage idea formation in this challenging task. This was done by helping students articulate their own ideas or by providing encouragement to persist through the openness of the task. The model-revision task used additional ways to *Build a Supportive Classroom Culture* that included encouraging students to share their data with other groups or to use data from other groups when constructing their final explanations (Make Ideas in the Room Accessible). This support occurred most commonly in one of two ways: through a general invitation for students to look at other groups' results or by directing a group to seek out results from a particular other group. The first is illustrated by this quote:

> I encourage you to look at other people's results as well as your own just because they might have ideas you want to include in your model.—Instructor 2

In this example, we can see that the instructor was creating a supportive environment by setting the classroom norm of collaborating across groups. She also took the time to explain to

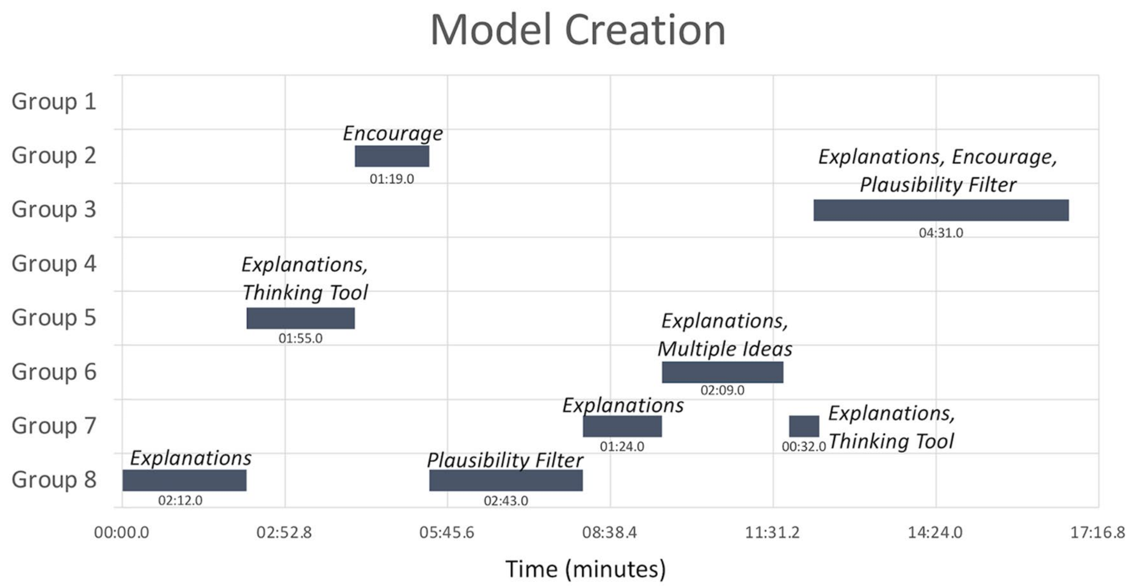

FIGURE 3. Timeline of in-class supports used by Instructor 1 in one model-creation task during the "Bacteria Growth" unit. Each episode is labeled with the total time of the interaction that the instructor had with a group of students and the in-class instructional supports coded for that episode. The instructional supports codes are labeled as "Explanations" (Focus on Explanations), "Encourage" (Encourage Emerging Ideas), "Thinking Tool" (Model Is a Thinking or Communication Tool), "Plausibility Filter" (Plausibility Filter), and "Multiple Ideas" (Multiple Plausible Ideas).

the students why it was beneficial for them to collaborate on their ideas to better refine their final models. Within other instances, the instructor made specific inquiries about another group's results to the students. For example:

> There is at least one group that is doing stuff that is a little different about the sensing, I think it was—have you looked at [group A's] results? [Students: Not yet.]. You might ask them what they are seeing so far because … they are taking a different angle on thinking about how they sense and signal … if they happen to have any results you might look at that because it is something different about how this sensing is happening.—Instructor 1

Here we can see that the instructor was recommending that this student group talk to another group in the room that had a similar hypothesis. The instructor emphasized the value of hearing another perspective about the data in the room, especially among groups who had similar thinking. We can see that the instructor often used this support to highlight other data in the room to students who may not have noticed the results or may have deemed them as not important.

In the results presented, we chose to highlight the supports most frequently used by these instructors. However, these instructors also used other supports to help their students in both of these tasks (Table 2). We present the results of this analysis in Table 2, which characterizes the different supports and how they align with the previously characterized instructor intention themes. Additionally, we report the occurrence of each support and intention theme to allow for better understanding of how commonly each support was used in each task. Table 2 thus highlights some similarities and differences in how supports were used between these two model tasks. In both the model-creation and model-revision tasks, instructors often seem to be acting upon their intention to *Build a Supportive Classroom Culture*. Because students were often hesitant to propose initial models during the model-creation task, instructors were more likely to encourage emerging ideas or help students to understand that multiple ideas were plausible. Instructors were also more likely to push students to visualize their ideas and to understand the purpose of models as a thinking and communication tool in the early stage of the model cycle. During model revision, instructors spent significant time supporting students' efforts to connect evidence to their models, a category that was not relevant during the model-creation task.

Connecting Instructor Intentions with Support Actions: Example from Modeling. To highlight the potential connections between an instructor's intentions for the modeling task and support actions, we present a case-based investigation of Instructor 1 during one class session. Figure 3 shows the episodes, or instructor–student interactions, that occurred during one model-creation task, which was 20 minutes of a 3-hour lab session. Instructor 1 interacted with six out of the eight student groups in this activity during this day, though she did visit all the groups at earlier points in this same class session. By looking at the instructor support actions shown in Figure 3, we can see how this instructor adapted her supports as she moved between groups. For example, we can see that the instructor used Focus on Explanations ("Explanations") in almost every episode but Encourage Emerging Ideas ("Encourage") occurred in only two episodes. Looking at when the support Encourage Emerging Ideas occurs during the task gives us insight into some of the different ways this support was used. The first Encourage Emerging Ideas occurred early in the task, when the instructor may have needed to provide the students with more assistance and encouragement as they were first formulating their initial ideas. The second instance of Encourage Emerging Ideas occurred in the last and longest episode this instructor had with students in the timeline. In this episode, we can see that the instructor used this support in conjunction with two other supports, which seemed to be in response to a group struggling to formulate an explanation.

Along with seeing which actions the instructor used to support students in different episodes, we can also look at Instructor 1's intentions. When asked to reflect on her intentions for this model-creation task for the unit shown in Figure 3, Instructor 1 stated:

> I was trying really hard to push people to actually do explanatory models because in this lab there is a tendency for students to kind of recapitulate the data; what they first give as a model is really kind of, "this is what happened," as opposed to, "this is what is going on to make this happen."—Instructor 1

In our analysis, we coded this response as *Encourage Modeling as a Cognitive Tool*. From her response, we see that this instructor intended to focus her students on drawing mechanistic explanations on this particular day. Figure 3 shows us evidence of how she carried out this intention through the supports Focus on Explanations ("Explanations") and Model Is a Thinking or Communication Tool ("Thinking Tool"). Additionally, we noticed that, to encourage students to build models, the instructor also had to validate and encourage student ideas ("Encourage"). By looking at the intentions for this specific task, we gain insight into what this instructor was hoping to accomplish with the actions we observed.

Instructor Supports in Experimental Design. From our analysis of the instructor intentions, we noted that the instructors' main goal in the experimental design task was getting their students to design an experiment that aligned with a question from their model.

As the instructors sought to *Check Alignment of Model and Data*, we noticed that they commonly directed students' attention back to their initial models to reorient them to the goals or questions they may want to address (Apply Use of Model). For example:

> Got it. So I'm going to back up a little bit and look at your models so I kind of—so if you could kind of draw the connection for me?—Instructor 1

Here, the instructor wanted to understand the students' initial models and ideas before assessing or responding to their proposed tests. Another way that the instructors emphasized alignment between tests and hypotheses was by specifically stating a group's proposed test and hypothesis back to the students with their assessment and validation that they fit together (Evaluate Alignment between Hypothesis and Test). For example:

> So you are thinking [of] adding the acid to the ATCC media? [Students confirm.] Okay. That makes sense to me. Cause your hypothesis is that A is, that the acid is what is causing the problem for E? Okay.—Instructor 2

Both of these supports focused on the instructor helping students navigate between the different modeling cycle tasks—in this case, by thinking back to the prior task of creating a model in order to be productive in the current task of designing an experiment.

Along with assessing for alignment between hypotheses and tests, the instructors intended to help students *Navigate the Practices of Experimental Design*. For example, the instructors worked to help students think through the results they would expect to see when they conducted a specific experiment (Reason Forward to Results):

> It's just kind of fun to start thinking about what could those proteins be doing? And if they are doing what you think, what might you see when you do your experiments?—Instructor 1

The instructors also worked to support students' reasoning about alternative results or explanations in interpreting their anticipated experimental results (Reasoning about Alternative Experimental Outcomes). For example:

> I'm just thinking hypothetically, where you would go in different places. So, if you see what you expect to see, then it straight up supports this. But if you see a mix of the opposite … What if neither of these grow without [it]—what would that tell you?—Instructor 1

Both supports, Reason Forward to Results and Reasoning about Alternative Experimental Outcomes, involved asking students to think about possible future outcomes; the second additionally directed students' attention toward alternatives as a way to evaluate what might be learned from the experiment.

As would be expected, the instructors also commonly helped their students understand the different experimental tools available (Support Understanding of Tools) and design controls (Support Thinking about Controls). Interestingly, instructors commonly helped their students' Reason Forward to Results as a way to support their thinking about controls. These supports often included the instructor reasoning forward to potential results to emphasize the roles played by controls and the types of controls needed for the proposed experiment. For example:

> Those are really good to do because let's say you do this, and you get negative results. It doesn't grow. Well, I could just say, "Well, maybe you just set up your cultures wrong," so you need to set up one that actually showed growth. On the other hand, if it does grow, I can say, "Maybe you just set up your cultures wrong." And you also need something that you expect not to grow.—Instructor 1

Here we have highlighted some of the in-class supports used by the instructors that were different from the modeling tasks and specific to the experimental design task. Similar to the model-creation task, there were many other supports that these instructors used to help their students in this task (Table 3). Characterized supports and their frequencies are presented in Table 3 and organized by their alignment with the instructor intention themes. Interestingly, we can see the intention theme *Encourage Modeling as a Cognitive Tool* was still a common theme in this task. Though the focus of this task

TABLE 3. Instructor supports and occurrence in the experimental design task[a]

Experimental design instructor supports		Percent Occurrence $n = 64$
	Instructor intention: *Check Alignment of Model and Data*	34%
In-class supports	**Evaluate Alignment between Hypothesis and Test** Instructor checks for a match between the experimental tool proposed by students and idea proposed. The hypothesis, experiment, and instructor assessment of alignment all must be articulated to the students.	27%
	Apply use of Model The model drawn by students from the previous activity is referred to or referenced by instructor. The includes the instructor asking the students to explain the prior model or draw out their new ideas.	17%
	Instructor intention: *Encourage Modeling as a Cognitive Tool*	24%
In-class supports	**Refine Hypotheses** Support students in articulating their current hypothesis. Instructor may check to see if the hypothesis is explanatory, clearly stated, and multiple ideas are distinguished.	16%
	Focus on Explanations Push students to fully explain ideas, often by asking follow-up questions to clarify ideas.	16%
	Instructor Intention: *Build Supportive Classroom Culture*	13%
In-class supports	**Encourage Emerging Ideas** Encourage student idea formation. Often includes encouraging initial formation of ideas, affirmation of having wrong ideas, and emphasizing student productive ideas.	13%
	Instructor intention: *Navigate Practices of Experimental Design*	59%
In-class supports	**Support Understanding of Tools** Instructor explains experimental tool options or provides further information about the tools that can be used by to test their experimental hypotheses.	42%
	Support Thinking about Controls Instructor guides students to think about controls they would need for analyzing data of their proposed test.	22%
	Reason Forward to Results Instructor supports students in thinking about the possible results that may get when they conduct their experiment. This includes helping the students think about the types of results that will be meaningful to their hypotheses, helping them evaluate what they be able to learn from their experiment, or modeling the process for their students.	17%
	Reasoning about Alternative Experimental Outcomes Support students in reasoning about alternative experimental outcomes or explanations about anticipated results.	6%
	Instructor intention: *Support Productive Efforts*	22%
In-class supports	**Encourage Expansion or Reduction of Test** Instructor assesses the time management needed by the students for the tests proposed. This often includes suggesting that students add or limit the tests they plan to conduct.	22%

[a]Instructor supports are organized within the instructor intention themes previously characterized. Percent occurrence identifies how many episodes the support was coded in out of the total possible episodes for the experimental design task ($n = 64$).

was not explicitly centered around building student models, the instructors still spent a significant amount of time focusing students on the explanations proposed in their models. The prevalence of this intention further highlights the connection of the three model-cycle tasks all working together to complete the larger goal of students building an explanation for the phenomenon.

Connecting Instructor Intentions with Support Actions: Example from Experimental Design. As with the previous task, we again highlight the connection between the instructor supports and instructor support actions, in this case, for the experimental design task. Figure 4 shows the episodes, or instructor–student interactions, that Instructor 1 had during one experimental design task, which was 58 minutes of a 3-hour lab session. The first thing that can be seen is that there were a greater number of both instructor–student interactions and instructor supports used during this task, in comparison to the modeling task. As the previous task, Instructor 1 continued to adapt her supports to meet the needs of each individual group, which can be seen by examining the different supports she used across the groups. Figure 4 illustrates that Instructor 1 supported her students during this task in thinking through the technical aspects of developing an experiment ("Controls," "Tools," and "Expansion/Reduction"). She also focused on helping students to develop their conceptual ideas throughout the task ("Hypothesis" and "Explanations"). Importantly, she also guided students in making connections between their conceptual ideas and how they conducted their experiments ("Alignment" and "Apply Model")

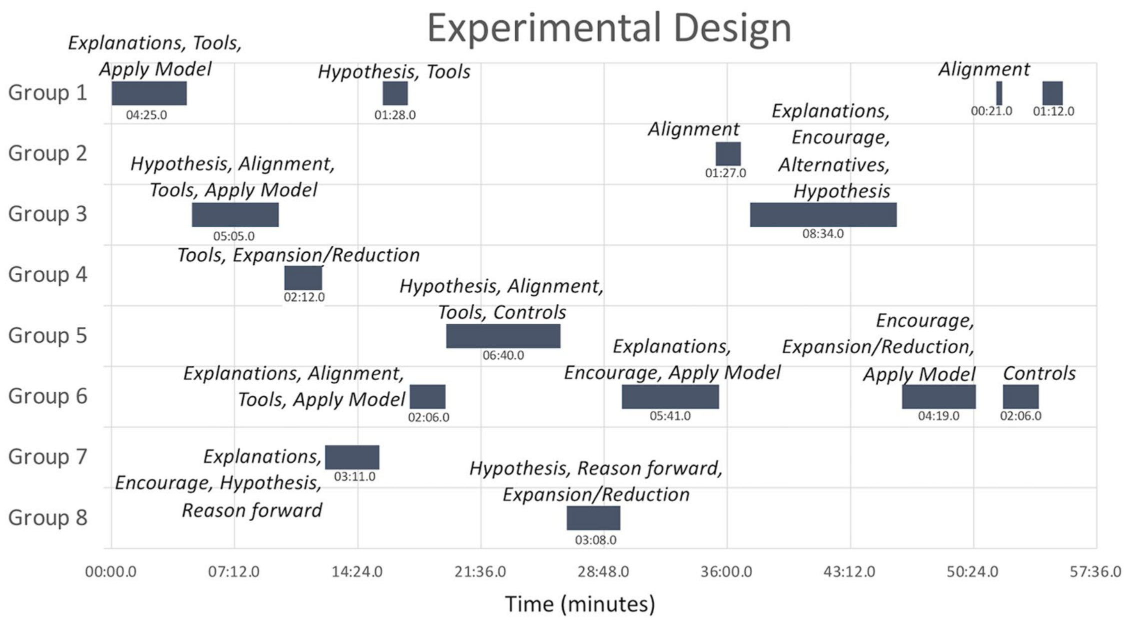

FIGURE 4. Timeline of in-class supports used by Instructor 1 in one experimental design task during the "*Chlamydomonas reinhardtii* Phototaxis" unit. Each episode is labeled with the total time of the interaction that the instructor had with a group of students and the in-class instructional supports coded for that episode. The instructional supports codes are labeled as "Explanations" (Focus on Explanations), "Encourage" (Encourage Emerging Ideas), "Alternatives" (Reason about Alternatives), "Hypothesis" (Refine Hypothesis), "Alignment" (Evaluate Alignment between Hypothesis and Test), "Tools" (Support Understanding of Tools), "Reason forward" (Reason Forward to Results), "Expansion/Reduction" (Encourage Expansion/Reduction of Test), "Apply Model" (Apply Use of Model), and "Controls" (Support Thinking about Controls).

Additionally, we wanted to connect Instructor 1's intentions for this task to the actions seen in Figure 4. When we asked her to reflect on her intentions for this specific unit of experimental design, she stated:

> To help them come up with—draw hypotheses out, that again, align with something in their model. So kind of say, "How can I use this model to like focus in?" … And to think forward about like what they are going to be able to say when they get their data … thinking back to *Chlamy* [unit] in particular this is the first time that we really are trying to lean on controls a little bit more and that's something that is really challenging and so a little bit of a focus for this one, at least in principle, is helping them think through the role of controls in their experiments.—Instructor 1

From the instructor's response, we can see that she viewed the students' models as a resource for conceptual reasoning during the process of experimental design. Specifically, she aimed to promote connections between model use and hypothesizing. Additionally, for this instructor, experimentation (from hypothesis formation through data interpretation) was a continuous process. Therefore, she aimed to guide the students to begin to reason about their potential results and the implications of controls during the design phase of experimentation. Given her intentions, it makes sense that Instructor 1 fluidly moved between many different instructional supports to help students with the technical and conceptual aspects of experimental design, while also emphasizing how these aspects of experimentation should be aligned. Our analysis reveals how the instructor's overarching intentions were aligned with how she supported students in this task. However, the fact that she adapts her use of supports to meet students' in-the-moment needs points to a more flexible and complex set of intentions. This raises new questions about the explicit connections and interplay between the instructor intentions and supports that could be the focus of a future study.

DISCUSSION

This study demonstrates the role of instructor reasoning involved in supporting students in the scientific practices of modeling and experimental design. Our results detail some of the ways in which an instructor can support the efforts of individual students during these tasks by flexibly responding to the needs of different students. Additionally, we uncovered what instructors were trying to accomplish, that is, the intentions behind their in-the-moment actions. The instructors in this study were found to have intentions that were well aligned with actions they used to support students. The instructor intentions provided crucial explanatory power for understanding the rationales for the teaching choices made.

Our study joins others that seek to deeply characterize the nature of instruction in undergraduate biology classrooms. The creation of observation instruments like COPUS have created a way to systematically code instructor actions (Smith *et al.*, 2013). However, COPUS is not designed to capture the nature of instructor discourse. More recent instruments, for example the Classroom Discourse Observation Protocol (CDOP), provide additional explanatory power by focusing on instructor dialogue and how it relates to student-centered and instructor-centered classrooms (Kranzfelder *et al.*, 2019). In a related study, Seidel *et al.* (2015) focused on "noncontent" instructor talk. These authors created an instrument that can provide insight into how instructors foster the social environment for learning. Importantly, the research questions and goals of a study are important determinants of how a researcher may choose to characterize classroom discourse. This point is illustrated in how Kranzfelder *et al.* characterized noncontent–related instructor discourse. All the instructor activities that would be captured by the Seidel *et al.* (2015) coding guide would presumably be characterized by the CDOP as, "no content discourse" or "other," because their instrument was focused on a different set of questions; namely, to understand how instructor dialogue helped students in learning biology content.

The questions that a study poses about instructor dialogue are influenced by the instructional context. Inquiry laboratories are a challenging context for instructors, requiring a frameshift toward supporting students in scientific practices. Our field has little insight into how instructors make this shift. Our questions, and thus our approach to characterizing instructor discourse, were focused on the ways in which instructors support students in scientific practices. Our focus on practices means that the questions we asked intersect with others' characterization of both content and noncontent dialogue. For example, one discourse category in the CDOP, "linking," focused on the instructor associating a past topic with a current topic when talking with students (Kranzfelder *et al.*, 2019). This discourse move is related to Apply Use of Model in our study, which captures instances in which the instructor calls attention to students' model drawings as they design an experiment, attempting to scaffold connections between these two tasks. In this way, our study provides specificity to the description of what the instructor is doing and may provide actionable insight into how to support students as they engage in science practices. Additionally, the noncontent instructor talk theme of "building a biology community among students" focuses on an instructor creating a space for students to collaborate and rely on one another as a resource (Seidel *et al.*, 2015). This theme is like the Make Ideas in the Room Accessible support in our study, whereby instructors encourage students to share their experimental findings with other groups. In this case, our results suggest how instructor dialogue that builds community is carried out to create a classroom environment that supports students in conducting their own inquiries.

In addition to characterizing instructor discourse, our study reveals the instructor intentions behind the ways in which they talk to students. For example, when looking at one intention theme more closely, *Build a Supportive Classroom Culture*, we can see how it was carried out in practice. Our results illustrated multiple support actions that were used to implement this one intention: Make Ideas in Room Accessible, Encourage Emerging Ideas, and Multiple Plausible Ideas. By looking at just one of these supports alone, we would not understand the unifying "why" behind their implementation. We would expect that this "why" would include instructor beliefs, prior experiences, instructor intentions, and ongoing interactions with students. By looking at instructor intentions, which is the aspect most proximal to the instructor support actions (Figure 1), we begin to uncover a part of the "why." Future studies could explore possible connections between instructor support actions, intentions, and beliefs.

Another finding of our study was overall alignment between the characterized instructor intentions and instructor support actions, that is, they carried out the actions that they had planned. The fact that instructors were the designers of the curriculum likely contributed to the alignment between intentions and supports. Though we saw overall alignment between instructor intentions and actions, there was still a need for instructors to flexibly adapt the supports used with each individual student in the moment. These two instructors used 18 different support actions during the modeling and experimental design tasks. Figure 3 shows one example of how one instructor flexibility adapted her supports during the model-creation task. Across these episodes, we can see that different combinations of instructional supports were used at different times. When we examined what was being said in each conversation, we saw that even the same action was used in different ways, depending on the context. We can conclude that supporting students through a scientific inquiry requires the instructor to react flexibly to address different problems and to navigate differences in the interpersonal and educational needs of each group of students (Schoenfeld, 2008; Hammer *et al.*, 2012; Gibson and Ross, 2016).

The Importance of Instructor Intent

As emphasized throughout this study, instructor intentions are a crucial part of understanding instructional actions. Our findings for research question one demonstrate five intention themes that instructors had for the modeling and experimental design tasks. Uniquely, our findings provide a first look at the rationale behind model-based inquiry implementation through the empirical investigations of in-the-moment intentions.

Current recommendations for designing more scientifically authentic curricula propose a multitude of important themes needed to effectively bring model-based inquiry to the classroom. First, there is a current emphasis on recommending that students use models to construct explanations about the natural world. Through the scientific practice of modeling, students are given agency to generate new ideas and make sense of their observations (Windschitl *et al.*, 2008; Passmore *et al.*, 2009; Hester *et al.*, 2018). Second, there is also an emphasis that inquiry curricula should foster an inclusive classroom environment, open to different ideas. Specifically, classrooms should include opportunities for student agency and collaboration about their scientific ideas (American Association for Advancement in Science, 2011; National Research Council, 2012; Miller *et al.*, 2018). Both recommendations are important for designing a successful model-based inquiry curriculum but are also important for the instructor to consider during implementation. Our instructor intention, *Encourage Modeling as a Cognitive Tool*, illustrates how curricula that include student modeling can be translated into practice. The instructors could intend to help their students use models by planning to push them to think about how to include mechanisms in their drawings or to revisit models to refocus on building explanations. Additionally, the instructor intention *Build a Supportive Classroom Culture* is another intention that aligns with the theme of creating an inclusive, collaborative classroom environment. We found that instructors intended to create a classroom environment where students felt comfortable by planning to encourage students to come up with their own ideas and by finding times when it was important to push students to share ideas collaboratively.

Through our investigation of instructor intentions, we uncovered new themes that instructors who are trying to implement authentic model-based inquiry curricula rely on. *Check Alignment of Model and Data* focuses on the instructor goal of helping students connect across the different model-cycle tasks. Instructors intended to help students think back to prior tasks or forward to future tasks in each of the model-cycle tasks. Specifically, they intended to support student understanding of how these different scientific practices work together to build an explanation, as scientific practice involves alignment of phenomenon, model, and data. For example, when students were designing experiments to test their models, instructors intended to help students think about how well their proposed tests aligned with hypotheses within their models. A study by Manz *et al.* (2020) brings into focus the importance of alignment among phenomena, data, and explanatory models in an inquiry classroom and recognizes the need for future work looking empirically at these alignments. Another new theme, *Navigate Practices of Experimental Design*, focuses on the instructor's intentions for students to understand the available tools, think about appropriate controls, and challenge students to reason forward to expected experimental results. Our findings provide new empirical information about how instructors can support students to productively engage in these scientific practices.

Addressing the Challenge of Inquiry Implementation

Previous studies have considered challenges students and instructors face in inquiry curricula. Our results for research question two relate to these studies and offer additional insight into how instructors might productively support students in the challenges of inquiry. Specifically, our work highlights practical ways in which an instructor can support students in the most difficult aspects of inquiry that have been identified in prior research studies.

Students Supporting Models with Evidence. Students face difficulty in supporting explanations with evidence. For example, Duncan *et al.* (2018) compared ways that experts and novices approached evidence and suggested that students would need support to make connections between a model and evidence. We found that our instructors commonly used Connect Evidence to Model to support students in thinking about different pieces of experimental evidence and how or if they might connect to their proposed models. On a similar note, the support Check Back to Prior Model or Hypothesis, was another way in which our instructors' helped students connect evidence to their models. In this support, the instructor was seen reminding her students to think about their model while they were analyzing experimental data. Both supports provide a practical way students can be supported in interpreting evidence and aligning experimental data to their models.

Students Generating Biological Mechanisms. Another challenge for students navigating inquiry is generating biological mechanisms (Duncan and Reiser, 2007; Duncan and Tseng, 2011; Van Mil *et al.*, 2013; Southard *et al.*, 2017). Southard *et al.* (2017) found that students struggled in hypothesizing a mechanism to connect multiple entities within a model. They found that instead students would often hypothesize a mechanism for only some components of a phenomenon. We found that our instructors commonly used Focus on Explanations as a way to help students think more mechanistically by asking them follow-up questions to clarify how they were thinking about the entities and modules in their proposed models. Another support we found the instructors used to support students in generating biological mechanisms was Encourage Emerging Ideas. The instructors were often found to be encouraging students' tentative ideas and assuring students about the process of scientific uncertainty. Many studies have reported that it is common for students to be uncomfortable with the scientific uncertainty that occurs in more authentic science curricula (Gafney, 2005). Our results demonstrate that instructors can support students in navigating this uncertainty by providing encouragement through the Encourage Emerging Ideas support, as mentioned earlier, or through the Multiple Plausible Ideas support, which also provides encouragement to the students but includes reminding students that there is not a single anticipated answer that they are expected to find at the end. Both supports are working to help the students feel comfortable with scientific uncertainty, which is important for them to generate a biological mechanism.

Beyond Thinking about Controls in Experimental Design. The final student challenge we will address is the act of designing experiments, which is recognized as a difficult task for students to do and for teachers to support (Dasgupta *et al.*, 2017). Studies looking at how students design experiments often focus on how students use and manipulate variables to create controls (Lin and Lehman, 1999; Arnold *et al.*, 2014; Dasgupta *et al.*, 2017). Our findings provide examples of how an instructor could approach supporting students in this aspect of experimental design through Support Thinking about Controls. When using this support, the instructor provided guidance to students to think about what variables need to be controlled based on their hypotheses and tests. In addition to helping students navigate controls and tools, our results draw attention to the need for instructors to support additional aspects of experimental design, those that involve initial formation of an experimental idea. For instance, the instructors in our study were also seen supporting students in developing hypotheses (Refine Hypothesis), aligning student hypotheses with tools (Evaluate Alignment between Hypothesis and Test), and helping students visualize possible results they would get if they conducted their proposed experiment (Reason Forward to Results). These other aspects of experimental design focus on the cognitive aspect of generating a hypothesis or question and thinking through the plausibility of different tools to test it. Though these aspects of experimental design are not highlighted in other classroom studies, we propose that they are equally important and deserve further consideration in understanding why this task is challenging for both students and instructors to navigate.

Instructional Implications

We see the potential for many of the challenges faced by instructors implementing inquiry curricula to be supported through the findings of this study. The characterized instructor intention themes and instructor support actions provide a detailed account for possible ways instruction can be enacted. We propose that thinking about these findings may help others in considering how inquiry is enacted in their own courses.

TABLE 4. Instructor implications

Instructor intentions findings	Questions to consider:
1. Inquiry instructor intends to help students connect across inquiry tasks (i.e., hypothesizing, designing tests, and building explanations).	– How can I scaffold students in navigating between inquiry tasks? – How do I help students maintain focus on the overall task of building an explanation?
2. Inquiry instructor intends to *Build a Supportive Classroom Culture*.	– How do I make students feel comfortable sharing ideas? – How do my conversations with students encourage them to have ownership of ideas?
3. Inquiry instructor intends to *Encourage Modeling as a Cognitive Tool* by emphasizing explanation building and visualizations and by valuing multiple diverse student models.	– What is the purpose of models in my classroom? – What ideas do my students' models reveal and is there a diversity of ideas?
Instructor support findings	**Questions to consider:**
4. Inquiry instructor supports students by explicitly inviting them to share ideas and collaborate across the classroom.	– At what points in the inquiry would it be most useful for my students to collaborate? – What structures are in place to create a need for collaboration?
5. Inquiry instructor supports students in designing experiments by asking them to reason forward to possible results and what they might mean.	– Will this student's proposed experiment address the student's inquiry question? – How do I help students learn to build and assess their own inquiries?
6. Inquiry instructor supports students in determining the scope of proposed experiments, often suggesting adding or eliminating experiments.	– Will students have time to complete an inquiry of this scope? – Will this student value and learn from this experiment, even if the predictions are not supported?

Table 4 includes some of the main findings from the characterized instructor intentions and supports that we think are important for inquiry instructors to consider. In addition to these findings, we have provided important questions to be considered as instructors think about how to apply these findings to their own instructional contexts. One of the main findings from this study (point 1 in Table 4) was the emphasis instructors placed on helping students to make connections across model-based inquiry tasks. We suggest that inquiry instructors should consider how they may support students to make connections between tasks. A related consideration is how an instructor may keep students' focus on the overall goal of building an explanation. Our findings suggest that this goal is an important organizing feature that may help students to engage in the diverse tasks and scientific practices of a model-based inquiry. Second, instructors in this study were focused on providing a supportive classroom culture and were often coded as explicitly inviting students to share ideas and collaborate (points 2 and 4 in Table 4). To foster this type of learning environment, instructors may wish to consider how they are making students feel comfortable about sharing ideas and how their curricula and instruction foster authentic collaboration. Finally, we point to findings from our study about specific intentions and supports related to the scientific practices of modeling and experimental design (points 3, 5, and 6 in Table 4). With regard to these practices, we suggest that it is important for instructors to consider specific aspects, such as the purpose of models, the alignment of experiments with a hypothesis, and the scope of students' proposed inquiries (see questions in Table 4). By providing the findings and questions in Table 4, we wish to emphasize the potential benefit of metacognitive reflection when implementing inquiry instruction. Such reflection should take into account both instruction intentions and classroom supports.

Limitations and Future Directions

While we argue that this research yields new insights into the complexity of the instructor's role in a model-based inquiry classroom, we also recognize the limitations in our study design. Though our design centers around the study subjects being designers of the curriculum investigated, there are limitations for this choice as well. The main concern is that these instructors have advantages that would not be present in a normal teaching population: prior experience teaching AIM-Bio, experience teaching other curricula, and diverse research experience in education and science. This study does not illustrate how instructors with less experience may successfully implement this curriculum in a different way. Additionally, the methodological approach used to capture instructor intentions has limitations, in that we cannot guarantee that the intentions reported after teaching are the exact same ones that instructors had in the midst of instruction. Also, we think it is important to recognize implications of how the instructional supports and intentions impact students. With limitations with IRB consent from students, our findings were framed and analyzed around the teachers' views and thoughts. This limited our ability to fully account for the students' reactions and ideas for many instances of analysis.

Our study points to the need for further development in understanding the instructor's role across diverse inquiry settings. Though we have characterized the instructor supports and intentions in this context, we have only begun to identify the interplay between these two components. Our study raises questions about the connections between individual instructor intentions and supports that could be addressed in a future study. Our study also draws attention to the potential influence of prior experiences and instructor frameworks on instructor intentions and actions for inquiry teaching. Our results have led us to hypothesize that the instructors in this study often used a research mentor framework when guiding students through scientific practices. With future work, we hope to further characterize the connections between these aspects of teaching and propose a holistic theory for model-based inquiry instruction. Additionally, future work is needed to understand connections between instructor actions and student outcomes. Specifically, understanding which supports and intentions are essential to student success would provide a needed resource in training instructors to produce desired student outcomes. Finally, as laboratory courses are often instructed by student instructors (TAs), further work is needed to understand how to support and train this specific instructor population to teach in an inquiry laboratory. We plan to apply the findings from this study to investigate the intentions and actions of instructors who are new to inquiry teaching.

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