How do Laboratory Teaching Assistants Learn to Support Science Practices? Exploring the Intersection Between Instructor Reasoning and Actions

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ABSTRACT

Undergraduate laboratory courses can provide opportunities for students to participate in science practices. This requires rethinking both curricula and instruction. Science practice–based courses require students to be positioned as epistemic agents, implying a shift in instructor role. Teaching assistants (TAs) are the primary instructors for laboratory courses. The current study aims to understand how TAs support students in science practices. Specifically, we sought to characterize variation in teaching and to understand how TAs learned and adapted their teaching approaches over time. Our study takes place in the context of a large, introductory laboratory course, Authentic Inquiry through Modeling in Biology (AIB-Bio). Our approach investigated the intersection between instructor reasoning and actions using stimulated-recall interviews, where instructors reflected on audio recordings from their classrooms. Application of our conceptual framework revealed that TAs' instructional roles and purposes were fluid and influenced how they supported students' science practices. We also showed how interactions with students cued fluctuations in TAs instructional approaches. Results include a case study that suggests potential mechanisms for TA learning. We propose a model to explain the variation in the enactment of a science practice–based curricula. We end with practical implications to consider when building professional development for science practice–based instruction.

INTRODUCTION

Our work in laboratory classrooms investigates a "science-as-practice" approach to instruction (Lehrer and Schauble, 2006; Ford, 2008). This approach shifts the educational focus from the products and procedures of science to the ways of participating in science. Prior research on the work of scientists (which has inspired the science-as-practice instructional approach) makes clear that legitimate science practices emerge from the interactions between members of a community of practice as they work to achieve a shared goal (Wenger, 1999; Ford, 2015). In a science class that embraces a science-as-practice approach, the shared goal of the community is to build evidence-based explanations of the natural world, that is, to construct scientific knowledge.

The literature describing successful learning in science practice–focused classrooms illustrates the crucial role of the instructor in framing students' legitimate participation as an epistemic agent. Drawing from prior work, we view an epistemic agent as an individual who proposes and evaluates knowledge and knowledge-building practices (Miller *et al.*, 2018). In other words, to foster students' classroom engagement in science practices, they must be positioned as having a role in building explanations through scientific investigations. Without this frame, instructors easily

Stanley Lo, *Monitoring Editor*

Submitted Mar 29, 2024; Revised Aug 6, 2024; Accepted Sep 19, 2024

CBE Life Sci Educ December 1, 2024 23:ar56

DOI:10.1187/cbe.24-03-0118

Conflicts of interest: The authors declare no conflicts of interest.

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fall into typical norms of teacher-imparts-knowledge rather than student knowledge construction through participation in science practices (Miller *et al.*, 2018).

The current study investigates how instructors support students in the scientific practice of modeling. It takes place in the context of a large-scale implementation of a curriculum that has been shown to evoke students' legitimate participation in scientific practice (Bolger *et al.*, 2021). We frame our investigation around the idea of **learning** by novice instructors, in our case laboratory teaching assistants (TAs). Ultimately, our study aims to shed light on a practical question: *How do we support novice teaching assistants in developing their approaches to science practice–based instruction?*

Laboratory Instruction by TAs

Redesigned laboratory courses can serve a critical role in broadening undergraduate access to research activities (Bangera and Brownell, 2014; Rodenbusch *et al.*, 2016). Such access, through reformed courses or mentored research experiences, has been shown to positively impact students' development as scientists (Nagda *et al.*, 1998; Jones *et al.*, 2010; Linn *et al.*, 2015; Hester *et al.*, 2018). However, large-scale implementation of research-based laboratory courses typically requires TAs to serve as the primary instructors, presenting unique challenges.

TAs have an increasing role in delivering undergraduate science instruction (Wyse *et al.*, 2014), with one survey finding that graduate assistants provide 91% of laboratory instruction at research universities (Sundberg *et al.*, 2005). However, TAs are often unprepared for the challenges of utilizing evidence-based teaching practices (Roehrig *et al.*, 2003). TAs may adopt the view that content knowledge is the only requirement for effective teaching (Luft *et al.*, 2004; Gardner and Jones, 2011). As members of traditional university culture, they may also believe that time spent on teaching responsibilities should be minimized in favor of research progress (Brownell and Tanner, 2012). Institutional structures may support these ideas, often providing insufficient professional development (PD) of graduate students in their role as instructors (Luft *et al.*, 2004; Austin and McDaniels, 2006). In a national survey regarding the preparation of biology teaching assistants, 52% of institutions required 10 or fewer hours of training, and only 40% required preparation meetings for laboratory instruction (Schussler *et al.*, 2015).

There are several studies that have investigated TAs' instruction in laboratories that have been redesigned to align with the processes of science more closely (Gormally *et al.*, 2011; Strimaitis, 2017; Grinath and Southerland, 2019; Duffy and Cooper, 2020; McFadden and Fuselier, 2020; Goodwin *et al.*, 2021). These studies point to several common observations. TAs were often found to be uncomfortable with the uncertainty of inquiry instruction, which influenced their teaching practices. Specifically, TAs were found to push students toward correct ideas, use forms of dialog that limit students' autonomy, and delegitimatize their scientific efforts (Grinath and Southerland, 2019; Duffy and Cooper, 2020; McFadden and Fuselier, 2020). Importantly, these studies suggest that there is significant variation in TA classroom instruction, with several reported cases of TAs promoting productive engagement in classroom science investigations. One study in the context of a CURE (Course-Based Undergraduate Research Experience) laboratory curriculum also points to important variations in how TAs view their role in the classroom (Goodwin *et al.*, 2021).

To understand the challenges of TA's instruction in laboratory courses, it is important to consider the fact that TAs are being asked to enact curricula materials that they did not design and often do not fully understand. An analogous situation in K-12 education is explored in studies of curricula "fidelity of implementation" (O'Donnell, 2008), providing several relevant insights. First the concept of an "enacted curriculum" recognizes the importance of viewing a curriculum not just as a set of educational materials, but instead as something that emerges from the interactions of teacher, students, and materials in a particular context (Ball and Cohen, 1996; Berland, 2011). Second, research on the fidelity of curricular implementation has revealed the importance of fidelity to curricular goals rather than to curricular procedures (McNeill *et al.*, 2018). In other words, the successful dissemination of innovative curricula requires us to consider the role of individual instructors' reasoning and how they adapt a curriculum through interactions with their students. This work has direct relevance for laboratory instruction by TAs, as documented tensions between a TA's view of instruction and that of a laboratory director have been shown to impede laboratory course reform (Duffy and Cooper, 2020).

While instructors' views may be misaligned with the curriculum they are asked to teach, it is also common for an instructor's thoughts about teaching to be misaligned with the teaching they carry out in the classroom. For example, a study of practicing science faculty revealed that despite self-reporting classroom reform after participation in a PD program, the large majority of faculty continued their traditional teaching methods of instruction (Ebert-May *et al.*, 2011). This suggests a misalignment between how faculty viewed their own instruction and how it was implemented. Another study showed how novice elementary school teachers implemented instruction that was only partially aligned with their stated beliefs about teaching (Roehrig *et al.*, 2009). This suggests a misalignment between beliefs about teaching and how those beliefs are translated into practice, especially for those learning to teach. These studies underscore the importance of external observations of teaching practice.

Despite the fact that an instructor's thoughts about teaching may be misaligned with their teaching practices, teaching beliefs are important influencer of teaching practice (Bryan, 2003; Crawford, 2007; Männikkö and Husu, 2019). Goertzen *et al.* (2010) demonstrated how different instructors may carry out the same teaching practice for different reasons, highlighting the importance of uncovering teachers' underlying thoughts and rationale. Taking these factors into consideration, our approach to understanding science practice–based teaching examines the intersection of a teacher's reasoning and classroom practice (Cooper *et al.*, 2022; Cooper and Bolger, 2023).

A Focus on Science Practice–based Instruction

While explicit efforts to rethink undergraduate teaching with a science-as-practice approach are relatively new, significant research in this area has been conducted in response to the 2013 release of the Next Generation Science Standards for K-12 education (e.g., Osborne, 2014; Manz, 2015; Berland *et al.*, 2016; Park *et al.*, 2022; Schwarz *et al.*, 2022). Additionally, there is a significant body of work demonstrating the success of this approach, which was the basis for the creation of the Next Generation Science Standards (NGSS) (e.g., Edelson, 1998; Stratford *et al.*, 1998; Lehrer and Schauble, 2006; Berland and Reiser, 2011; National Research Council, 2012). A key theme that emerges from this literature is how a science-as-practice approach differs from other forms of science teaching and the tensions that this can create.

The science-as-practice approach has been informed by research of social scientists investigating the work of biologists, chemists, and physicists (e.g., Dunbar, 1999; Latour, 1999; Morrison and Morgan, 1999; Nersessian, 2010). The picture of science that emerges is not one of a lone scientist carefully following a linear set of logical steps, as might be suggested by lessons on the "scientific method." These studies also show that science cannot be distilled into a set of actions or skills, that might readily lend itself to a guide for educators to teach these skills to students. Instead, science practices (i.e., the ways that scientists operate in practice) emerge from the social interactions of members of scientific communities (e.g., labs, groups, departments, disciplines) as they work toward shared goals of explanation (Wenger, 1999; Ford, 2015). Members of scientific communities develop ways of operating to meet their evolving needs as science progresses. Importantly, the community also functions to evaluate the evidence for new ideas that are generated (by the community). Thus, individual scientists play a necessary dual role of one who "constructs" and "critiques" knowledge claims, roles that are central to the epistemic work of the community (Ford, 2008).

With this view of science practice in mind, the literature suggests several ways that classrooms must change in order to adopt a "science-as-practice" approach. **First**, classroom goals should shift from a knowledge-product view of science to one that focuses on students' science participation. This can be a challenge when teachers continue to implement a traditional focus of conveying science knowledge products to students. These conflicting goals limit students' legitimate participation in science practices (Guy-Gaytán *et al.*, 2019). **Second**, instructors should view classroom activities through the lens of making epistemic participation meaningful to students. Science practice–based reforms have been criticized for falling short of this goal (Miller *et al.*, 2018). Instructors' dialog with students can send many, often contradictory, messages about epistemic agency, often falling into traditional teacher-dominated patterns of interaction (McNeill *et al.*, 2017; Russ, 2018; Guy-Gaytán *et al.*, 2019; Ke and Schwarz, 2021). **Third**, traditional classroom norms can no longer guide decisions about how to structure students' activities. Teachers may simplify what students are asked to do within science practice–based curricula so that their activities may fit into more familiar classroom structures, such as a guided activity or whole-class dialog (Jiménez-Aleixandre *et al.*, 2000; Ke and Schwarz, 2021). These examples of instruction preserve some of the surface features of science practice, but lack the deeper scientific meaning and forms of student participation that would indicate legitimate "practice."

CONCEPTUAL FRAMEWORK

We developed a conceptual framework that could explain how instructors might enact science practice–based instruction. A conceptual framework aims to connect across bodies of literature, including established theories, in novel ways. We drew from available research about the scientific practice of modeling, modeling in science classrooms, and teaching modeling and science practices. This differs from a theoretical framework in that it includes both established theories and our own emergent ideas, detailing relationships between key constructs (Miles and Huberman, 1994; Luft *et al.*, 2022). Similar to a theoretical framework, our conceptual framework provided a lens that guided our data collection and analysis. We will next unpack our conceptual framework by first detailing the science practice of modeling. We will then describe two dimensions of teaching science practice–based instruction, Instructional Purpose and Instructor Role, drawing from relevant work on students and teachers navigating science practices.

Our work is focused on the scientific practice of modeling. Evidence from studies of scientists' work, points to the use of models as thinking tools for the development of new ideas in science, including mechanistic models in molecular and cellular biology (Dunbar, 1999; Darden, 2002; Nersessian, 2002; Odenbaugh, 2005; Van Mil *et al.*, 2013). How scientists gain knowledge in biology is a complex interaction between data and model (Passmore *et al.*, 2009). Models are among the most generative and frequently critiqued objects produced by scientists. Thus, the scientific practice of modeling is at the heart of the epistemic work of biologists. Drawing from the philosophy of science literature (in particular Suárez 2010), Gouvea and Passmore (2017) articulated two ways of thinking about modeling in the science classroom. The first, a "models of" perspective, focuses on the model as a static representation of a particular phenomenon. For example, there is a model of the structure of DNA or a model of the mechanism of DNA replication. By contrast, a "models for" perspective focuses on the scientific purpose of a model. This conception of a model takes into account the epistemic agency of the person building or using the model. A model could be used by a scientist for many purposes (e.g., predicting, explaining, or evaluating evidence) and without such a scientific purpose a model, from this perspective, is useless.

Building on this perspective of modeling, we identified two dimensions for examining science practice–based instruction. We selected these two dimensions because they are central to a science-as-practice instructional approach and because they relate to known tension points for enacting this approach.

Dimension 1: ***Instructional purpose.*** We conceive of *Instructional Purpose* as the extent to which an instructor seeks to support classroom engagement in science practices. Because we are interested in the intersection of teacher reasoning and practice, our focus is not on an instructor's overall goals or beliefs, but rather on the instructor's underlying rationale for in-the-moment classroom interactions. This conception draws from prior work investigating the responsiveness of a teacher as they attend to the substance of students' ideas through dialog (Richards and Robertson, 2015; Grinath and Southerland, 2019). In our view, the *Instructional Purpose* is flexible to different classroom interactions and can in some sense be seen as arising out of interactions with students.

In our framework, we conceptualize of *Instructional Purpose* as moving between science practice–focused and content-focused instruction. A content-focused purpose relates to equating a "model" with a static representation, devoid of the epistemic activities of modeling (Gouvea and Passmore, 2017). In this way, an instructor is taking a "models of" perspective, which is not aligned with a science-as-practice approach to teaching. Canonical models (like the model of DNA) are the emphasis of almost every science textbook and instruction often focuses on helping students to understand this type of model. By contrast, a science practice–focused purpose takes a "models for" perspective, in which an instructor emphasizing student engagement in modeling practices. For example, when students are working to relate their experimental results to their model, they may be unsure and try to ask the instructor whether they got the "answer." An instructor using a "models for" perspective would not tell the students if they did or not interpret and relate their data to the model correctly but might instead scaffold the students to compare their current ideas to their initial hypotheses. This is because the instructor's purpose in this moment would be to support the students engaging with this science practice, not to assess whether they "got the answer" (Cooper and Bolger, 2023).

Dimension 2: ***Instructor role.*** We conceptualize the *Instructor Role* as the ways an instructor aims to position themselves, relative to their students, in classroom interactions. This conception stems from a social constructivist view of teaching and learning, which informed our conception of this dimension (Scardamalia and Bereiter, 1991; Amineh and Asl, 2015). A constructivist view has implications for how an instructor interacts with their students through dialog. Prior work on instructor's communicative approach expands on the forms of dialog that might be important to foster students' construction of ideas (Scott *et al.*, 2006). Specifically, an "authoritative approach" seeks to focus students' attention on just one meaning (typically that of the teacher or one approved by the teacher), in contrast to a "dialogic approach" which seeks to recognize and take into account multiple points of view. The later is more in line with a constructivist view.

In our framework, we conceptualize of *Instructor Role* as moving between student-centered and teacher-centered instruction. A student-centered role is one in which the instructor aims to position themselves as a support for students' construction of scientific knowledge, acknowledging and building from students' diverse ideas. This is in contrast to a teacher-centered role, in which the instructor aims to direct and control students' thinking, often monitoring students' ideas for correctness and asserting their own ideas in dialog. Gouvea and Passmore (2017) explain that a "models for" perspective emphasizes that the students are the ones using models for a scientific purpose (e.g., predicting or explaining). This requires the students to participate as epistemic agents. Thus, the teacher's role is to provide students with autonomy while also holding the classroom community accountable to the norms of the scientific discipline (Gouvea and Passmore, 2017). This perspective of science practice–based instruction is in line with a student-centered *Instructor Role*.

RESEARCH APPROACH

Our study takes place in the context of a large-scale implementation of a science practice–based laboratory curriculum by undergraduate and graduate TAs. In an effort to understand the variation of curricular implementation, we focused on the intersection between TAs' reasoning and their classroom practice. By closely examining individual TAs' instruction over time, we aimed to understand not only variation in teaching but also how novice TAs might learn and adapt their approach.

In this context, we asked the following research questions:

1. **How is the enactment of a science practice–based curriculum modulated by an individual TA's *Instructional Purpose* and *Instructor Role*?**
2. **In what ways can TAs learn to navigate science practice–based teaching over time?**

To address our first research question, we collected audio recordings of TAs as they interacted with students during modeling tasks. We then selected and played audio clips for TAs during interviews in order to stimulate their reflections on their own teaching choices (a stimulated recall approach, Calderhead, 1981; Shkedi, 2005). We then conducted a qualitative coding analysis, guided by our conceptual framework.

Because our goal was to understand variation across science practice-based teaching, we wanted to select clips from tasks that would be likely to engage TAs and students in science practices. We included tasks that we had previously demonstrated to have potential for rich scientific sense-making and student epistemic agency (Bolger *et al.*, 2021; Cooper *et al.*, 2022; Cooper and Bolger, 2023). Tasks were: 1) Students designing an experiment to test an explanatory model that they had previously generated and 2) Students evaluating and revising their models after collecting experimental evidence. Important to our study design, tasks were held constant across TAs.

To address our second research question, we used a case study approach to analyze the instruction of one TA whose initial *Instructional Purpose* and *Instructor Role* were similar to many other TAs. This approach allowed us to build an in-depth understanding of the potential mechanisms of instructor learning over time.

MATERIALS AND METHODS

Study Context

TAs taught a one-semester, model-based inquiry introductory biology laboratory course called "Authentic Inquiry through Modeling in Biology" (AIM-Bio) (Hester *et al.*, 2018). AIM-Bio is a 3-h weekly laboratory course in molecular and cellular biology. TAs teach between one to two sections with the average class size being 24 students per section. TAs act as the lead instructor for the laboratory section, under the guidance of the laboratory director.

The AIM-Bio curriculum was designed to bring authentic science practices into the classroom through student participation in "cycles of modeling" (Hester *et al.*, 2018). In the cycle, students are first introduced to a puzzling biological phenomenon and tasked with building a model explanation. In the following week, students design experiments to test their ideas and carry out their experiments. In the final week, they collect their results, share their experimental findings, and revise their initial models using the collected experimental evidence in the classroom. The curriculum relies on students having and testing different explanations for the same biological phenomena. This creates a genuine "need" to collaborate and share data as a community of scientists. Our previous work has described ways students legitimately engage with science practices as they grapple with uncertainty and integrate diverse ideas (Bolger *et al.*, 2021). Students completed individual lab write-ups at the end of each modeling cycle unit, where they reported on their data and provided a narrative comparing their initial and revised models using evidence that explained why their models changed. TAs assessed these lab write-ups using a rubric that focused on evaluating the evidence-based nature of students' arguments, not the correctness.

TAs participated in a presemester and weekly PD training during their semester of instruction. The presemester training consisted of two, 6-h days that prioritized introducing the TAs to the curriculum. This included framing the goals of the AIM-Bio curriculum and providing opportunities for the TAs to experience for themselves how this curriculum would be different from the traditional laboratory courses they had previously taught or experienced as a student. The weekly, 3-h training further supported these goals while also reviewing the tasks or activities that they would need to teach each week. Our overall goal in developing our PD course was to move beyond "just in time" preparation and instead prioritize developing the TAs as learners themselves. To accomplish this, we focused on including activities that supported the TAs own learning about science practices, pedagogical strategies, and provided opportunities for TAs to reflect on their own or others' teaching.

Research Subjects

TAs were recruited during the Spring 2020, Fall 2021, and Spring 2022 semesters. The AIM-Bio introductory biology laboratory course is taught by both undergraduate and graduate student instructors. Undergraduate students are required to successfully complete the course and preceptor the course for one to two semesters before becoming a TA. Preceptors work as assistants to the TAs (who are lead instructors), typically circulating during class periods to assist students with laboratory work, but rarely directing instruction at the whole-class level. Due to this requirement, all undergraduate TAs were juniors and seniors. For each semester, TAs were recruited the week before the semester began, during the presemester training described previously. TAs were verbally told about the research study and participation by one of the researchers (A.C.) and invited to participate. Across the three semesters of recruitment, 19 total TAs volunteered to participate in the research study (Table 1). The TAs in our study population are diverse in their previous teaching and research experience. One TA had up to 18 semesters of previous teaching experience while many other individuals were teaching for the first time. Note that we did not include time spent as a preceptor as teaching experience, although this role did provide an opportunity to interact with students. A similar trend is seen for research experience, two graduate student TAs had seven to eight semesters of research experience, with again, a few TAs who had never participated in scientific research.

Case Study Subject Selection. To investigate learning over time, we chose to conduct a case study analysis (Tellis, 1997; Yin, 2014). One TA, Aria, was selected as our case study subject for several reasons. First, she was one of the few TAs in our study who taught AIM-Bio for multiple semesters (four TAs met this criteria). Second, she was one of the few multi-semester TAs that was not missing any data (two TAs met this criteria). Finally, through our initial analysis of these two TAs, Aria was found to have "representative" semesters. Meaning, we found that the other TA being considered was an "outlier" in that she was impacted by factors outside of the study. We determined that these factors were affecting her teaching and learning in a way that would not allow for her case to explain ideas to a wider population (Yin, 2014).

Our chosen case study subject, Aria, was an undergraduate TA who joined the study at the beginning of her junior year. Her first semester in this study was also her first semester as a TA, though she had 1 year of previous experience as a preceptor for a traditional, introductory biology laboratory (not the AIM-Bio curriculum). Aria took the AIM-Bio curriculum as a student, but

TABLE 1. TA background information

TA	Undergraduate/ Graduate student	Year	Previous teaching experience (semesters)	Previous research experience (semesters)
Mason	Graduate	3	3	7
Quinn	Graduate	2	2	5
Oliver	Graduate	2	18	4
Juliet	Graduate	1	5	4
Violet	Graduate	2	7	8
Alice	Undergraduate	Junior	1	0
Logan (1)	Undergraduate	Junior	1	4
Theo	Undergraduate	Senior	1	1
Grace	Undergraduate	Junior	2	2
Aiden	Undergraduate	Senior	3	0
Betty	Undergraduate	Senior	5	1
Aria (1)	Undergraduate	Junior	0	0*
Ellie (1)	Undergraduate	Senior	0	4
Maya (1)	Undergraduate	Junior	0	2
Cleo	Undergraduate	Senior	3	2
Jack	Undergraduate	Junior	1	3
Olivia	Undergraduate	Junior	1	2
Jane	Undergraduate	Junior	1	4
Mia	Undergraduate	Junior	1	2

*Indicates TA who just joined a research laboratory the semester of data collection.
(1) indicates background information for the TAs' first semester of participation in the study.

she only experienced the first half of the curriculum as it was interrupted by COVID-19. During her first semester of joining this study, she also joined a research laboratory on campus as an undergraduate researcher.

Data Collection and Analysis

We acknowledge our positionalities as authors, recognizing that our backgrounds and roles in this project may have influenced our interpretations of the data. All four authors had prior experience teaching the AIM-Bio curriculum and brought those experiences as a lens with which we viewed teaching in this context. M.B. and S.H. were the designers of the AIM-Bio curriculum; M.B. and A.C. were the designers of the PD curriculum that was used to support teaching assistants who participated in this study. These experiences provided important insights and influenced our perspectives during research activities. Finally, M.B. served as PD facilitator for the subject in the research study, which meant that she had a mentoring relationship with the subjects during the process of data collection. A.C. and J.O. had a more objective, research-focused role during the process of data collection. The study subjects knew A.C. as a researcher and observer (and not as a facilitator) during PD. This provided credibility and separation to A.C. for purposes of obtaining informed consent from subjects and collecting data. A.C. and J.O.s' role also provided them with an additional level of objectively for data analysis.

Research Question 1. Instructor interviews were collected from TAs in Fall 2020, Fall 2021, and Spring 2022. The analysis focused on TA interviews from a single timepoint, after the "Bacteria Growth" unit, during their semester of instruction (Hester *et al.*, 2018). Interviews were audio-recorded and conducted within 2 wk of the end of the unit. For the Fall 2020 semester, data were collected 1 wk before our campus was closed due to the COVID-19 pandemic.

Instructor interviews were designed as semistructured, stimulated-recall interviews (Calderhead, 1981; Shkedi, 2005). Each interview protocol consisted of three different parts. The first part asked TAs to reflect on their general task goals or intentions for each part of the modeling cycle (i.e., model creation, experimental design, and model revision) for the unit they had finished teaching. The second part of the interview was the stimulated-recall portion. To carry out this approach, we collected in-class audio where TAs wore a microphone attached to an audio recorder during all laboratory sections instructed. Using this audio, two, 1- to 4-min audio clips were chosen for each model cycle task (model creation, experimental design, and model revision) and were played out loud for each TA during their interview. After listening to each clip, TAs were asked open-ended questions to better understand the rationale behind their instructional choices (Supplemental Table S1). In-class audio clips were chosen to specifically evoke reflection and generally focused on episodes that demonstrated representative instruction for that TA. The third part of the interview included asking the TAs two to three reflective questions that aimed to better understand their framework and ideas about teaching.

Drawing from our conceptual framework, we developed an a priori qualitative coding guide to measure TAs curricular implementation along two dimensions: *Instructional Purpose* and *Instructor Role*. The first dimension captured how a TA focused their instructional approach on engaging students in science practices or other goals (Table 2). The second dimension captured

TABLE 2. ***Instructional Purpose*** **coding guide**

Instructional purpose	Definition
Practice-focus	TAs are working to support students in doing things that make sense scientifically and allow for their engagement in doing science. This code requires at least one back-and-forth between the TA and student that supports a practice (not just a check-in about the task).
Combination	TA actions and/or reasoning include both practice- and content-focused aspects.
Non-practice-focus	TAs are working to move students toward a specific idea/concept/test that is not one the students have. This code can also include TAs that are focused on students completing the "task" assigned, rather than supporting cognitive engagement with the practice.

the extent to which TAs took on a student-centered role in their classrooms (Table 3). We also created a "combination" code for each dimension, if, for example, a TA took on a teacher-centered and student-centered role within a single codable episode. Examples of each code will be illustrated in the *Results* section.

Two researchers (A.C. and M.B.) applied the coding guide to the stimulated-recall portion of the instructor interviews for the experimental design and model revision tasks. We chose these two tasks because our preliminary analysis suggested that there was greater variation in implementation, in comparison to the model creation task. We defined an "episode" as including both the in-class audio clip and the TA's reflection about the clip. The two researchers first listened to a subset of data together (six interviews, resulting in 24 episodes) to practice applying the developed codes and agree on definition meanings. The two researchers then independently coded the remaining episodes for both the *Instructor Role* and *Instructional Purpose* dimensions ($n = 57$ episodes total). Each TA had four clips (two per model cycle task) that were included in our results. The two coders applied the coding scheme on the remaining TAs; coding disagreements were discussed until a consensus was reached. Additionally, Cohen's kappa was calculated to correct for chance occurrences of agreement between coders. The Cohen's kappa calculation included codes that the researchers agreed were present as well as the codes that they both agreed were not present per standard practice. Cohen's kappa was calculated to be $k = 0.67$, indicating substantial agreement (Cohen, 1960; Landis and Koch, 1977). The results will present the consensus results for all TAs, including the practice set.

Finally, we created scores for the *Instructional Purpose* and *Instructor Role* using the agreed-upon consensus coding results. The teacher-centered role and non-practice-focus purpose were given a score of 0, "combination" codes for role and purpose were given a score of 1, and the student-centered role and practice-focus purpose were given a score of 2 (Table 4). Each TA received a score out of 8 for both their *Instructional Purpose* and *Instructor Role* (up to 2 points for each of four episodes). TAs that were missing audio and did not have four clips, had their score normalized to be out of a total of 8 for both dimensions.

Research Question 2. We chose to conduct a longitudinal, explanatory case study on a single TA, Aria, over two semesters of instruction (Yin, 2014). We prioritized collecting multiple data sources, over time. As previously described for research question 1, we collected in-class audio and instructor interviews. Aria's in-class audio was collected for all of her instructed classes during

TABLE 3. ***Instructor Role*** **coding guide**

Instructor role	Definition
Student-centered	TAs express value for their students' ideas and individual students' successes (or their actions suggest this value). This may include the TAs actively listening to their students' ideas, encouraging, or asking open-ended questions to understand and refine student thinking.
Combination	TA actions and/or reasoning includes both student-centered and teacher-centered aspects.
Teacher-centered	TAs view their role as controlling the direction of the student learning, tasks, or ideas. This can include TAs correcting, inserting own ideas, mini-lectures, leading questions, or IRE.

TABLE 4. Scoring rubric for ***Instructional Purpose*** **and** ***Instructor Role***

Instructional purpose	Instructor role	Score
Content-focus	Teacher-centered	0
Combination	Combination	1
Practice-focus	Student-centered	2

the Fall 2021 and Spring 2022 semesters. Additionally, two instructor interviews were collected each semester, following the "Bacteria Growth" and "*Chlamydomonas reinhardtii* Phototaxis" units which we have described previously (Hester *et al.*, 2018). Thus, data collection captured her teaching at a total of 4 timepoints, over two semesters.

Our approach (which we will describe in detail next) aimed to address measures of quality, including construct validity, internal validity, external validity, and reliability (Yin, 2014). To address construct validity, we used multiple sources of evidence and analysis including stimulated recall interviews, in-class instruction audio, in-class support coding, instructor intention analysis, and *Instructional Purpose* and *Instructor Role* analysis. To address internal validity, we used an iterative methodological approach to reduce bias (Yin, 2014). Two researchers analyzed all the data individually and holistically, discussing themes, evidence, and claims through an iterative process that allowed for biases and discrepancies to be checked throughout. Our design addressed external validity through our choice to investigate Aria for our case, as she was the most "representative" subject which could allow for analytic generalizations about learning to teach science practice–based instruction (Yin, 2014). Finally, we sought to increase the reliability of our findings by carefully documenting our analytical process and sharing our approach.

The first step of our analysis was to establish the ways Aria supported science practice–based instruction. To do this, we applied our previously developed instructor intention and instructor support coding guides (Cooper *et al.*, 2022). Two authors (A.C. and J.O.) applied both coding guides to a subset of the TA data to establish the validity of the instrument with this new instructor population (TAs) and to refine or add themes. The resulting adapted instructor intention coding guide (Supplemental Table S2) was applied independently by the two researchers to Aria's responses to the first part of her interviews, the general task intentions for each model cycle task ($n = 12$ responses). Two independent coders (A.C. and J.O.) applied the coding scheme to all data. Cohen's kappa was calculated to be $k = 0.84$, to correct for chance occurrences of agreement between coders (Cohen, 1960; Landis and Koch, 1977). Similarly, the two researchers applied the adapted instructor support coding guides (Supplemental Tables S4, S5, and S6) to transcripts of Aria's in-class audio for the model creation, experimental design, and model revision tasks. As described in our previous work, episodes of teacher-student interactions were coded within each task (Cooper *et al.*, 2022). In total, 99 in-class episodes were analyzed across the two semesters Aria taught ($n = 36$ episodes in model creation, $n = 35$ episodes in experimental design, $n = 28$ episodes in model revision). The same two coders (A.C. and J.O.) applied this coding with a Cohen's kappa calculated to be $k = 0.82$ (Cohen, 1960; Landis and Koch, 1977).

The next stage of our case analysis was to take a deeper look at the ways Aria's teaching changed over time. We focused our attention on the instructor interviews. Two authors (A.C. and M.B.) listened to all three parts of each of her four interviews. Both authors noted Aria's reasoning and actions within and across interviews, paying special attention to changes. After discussing their observations, A.C. created analytical summaries immediately after each meeting. These summaries captured the agreed-upon ideas for all three interview parts, with more detailed notes given to the stimulated recall clips. Specifically, the summaries separately detailed the nature and/or actions of Aria's in-class interaction with her students and her stated rationale for each moment as these areas of the interview were the most complex. The analytical summaries were critical in capturing the author's discussion about Aria's case and facilitating a holistic understanding of her teaching over time.

The authors then systemically reviewed all the analyzed materials to build Aria's case, including her *Instructional Role* and *Instructor Purpose* coding results. The claims for Aria's case were chosen to illustrate the ways Aria learned over time. All claims presented were agreed upon by both authors (A.C. and M.B.).

RESULTS

Research Question 1: How is the Enactment of a Science Practice–based Curriculum Modulated by an Individual TA's Instructional Purpose and Instructor Role?

Based on our review of the teacher implementation literature, we hypothesized that the TAs in our study would have different implementations of the model-based inquiry curriculum. Specifically, we hypothesizedthat TAs would have variable *Instructional Purposes* and *Instructor Roles*, and that these dimensions, while related, would be distinct. We investigated the ways that TAs' *Instructor Roles* moved along a teacher-centered to student-centered dimension. Additionally, we investigated the *Instructional Purpose* of TA's interactions with students, focusing on the extent to which this purpose was to engage students in science practices. We begin with an example to illustrate the nature of our data and our analytical approach. After, we will present the variation in *Instructional Purpose* and *Instructor Role* across our TA sample. Finally, we demonstrate how this variation, within and across TAs, impacted the implementation of science practice–based instruction.

Instructional Purpose and Instructor Role were Inferred from a Combination of Classroom Interactions and the TAs Reflections on those Interactions. To understand how TAs supported students in a science practice–based curriculum, we examined their classroom actions and their reflections on those actions, evoked during stimulated-recall interviews. The following is an example of a TA, Ellie, as she interacted with students during a model revision task. The students were asked to work in groups to draw a new explanatory model for a bacterial growth phenomenon (growth of bacterial species "A" and "E"). Prior to this episode, they had collected data from an experiment they designed and had talked with other groups who had conducted different experiments. Students' words are paraphrased.

Ellie: What are your thoughts?
Student 1: [Explain that model will show how bacteria species A physically breaks down colominic acid to survive. The student is unsure if bacteria species E is unable to break down the colominic acid or if they just cannot use it to grow.]
Ellie: So how- how do you think [species] A is able to break down the acid?
Student 1: [They are unsure but discuss an idea they heard from another group where proteins could be picking apart molecules in the acid.]
Ellie: So some- did you, did you have any thoughts on how [species] A might be breaking down the acid or-?
Student 2: [They propose an enzyme or protein as a possibility]
Ellie: Yeah. Is it something that it is releasing? Or is it something that is internal? Or have you-
Student 1: [They are unsure and discuss another group's experiment and hypothesis where they believe species E survives off the byproduct of the acid that species A breaks down. However, the student is not fully convinced by the groups one test-]
Ellie: You're not like sold on-
Student 1: [They are unsure if the group used enough colominic acid to prevent E from growing-]
Student 3: [Another student interrupts to recall that this was the idea from their initial model]
Students: [They confer across groups members about their initial model]
Ellie: How does- based on your data when you did [medium] ATTC3 with colominic acid with [species] E did it live?
Student 1: [no]
Ellie: So then would it have- then how do you think that could affect your thinking maybe?
Student 1: [They really like the idea that the colominic acid prevents growth and that when the acid is added to the rich medium, ATTC3, growing would be prevented-]
Ellie: Okay so-
Student 1: [-but data from another group found that the acid is broken down when it is with species A or had previously been with species A, allowing species E to survive]
Ellie: So to mean it kind ofsounds like you are switching from [species] A can break it down to [species] A can make a byproduct?
Students: [Confer amongst group]
Ellie: I'll let you guys discuss.

In this example, we can see that the students are attempting to decide on an explanation that would best account for their collected evidence. Student 1 expresses uncertainty and the group of students does not all immediately agree on a model. Ellie engages with the students' sense-making process, prompting for reasoning (lines 5, 8–9, 11–12), highlighting student ideas (lines 30–31), and suggesting consideration of experimental evidence (lines 21–22). Throughout the episode, she remains focused on advancing the students' ideas and assisting them with the science practice at hand (model revision). Next, we asked Ellie to reflect on her rationale during this episode of instruction:

"I think I was trying to see if they could get on the same page in terms of if the colominic acid was necessary or if it was like the thing that was killing [species] E. And I thought maybe bringing up apiece of their own data might make them confer a little bit, but, I was like, OK, it's been different things like, yeah, yeah, like neither of their thinking is necessarily wrong. . . And it seemed like they were kind of at this like standstill going back and forth. So, I thought maybe more evidence will help." -Ellie

Ellie's reflection confirms that her in-the-moment goal was to help her students use evidence from data to build their own model. Her reflection further revealed that she felt that her students were "at a standstill" trying to decide between two models. She made the decision to direct the students to further consider experimental evidence, in hopes that it would cause these students to collaborate and move forward in their sense-making.

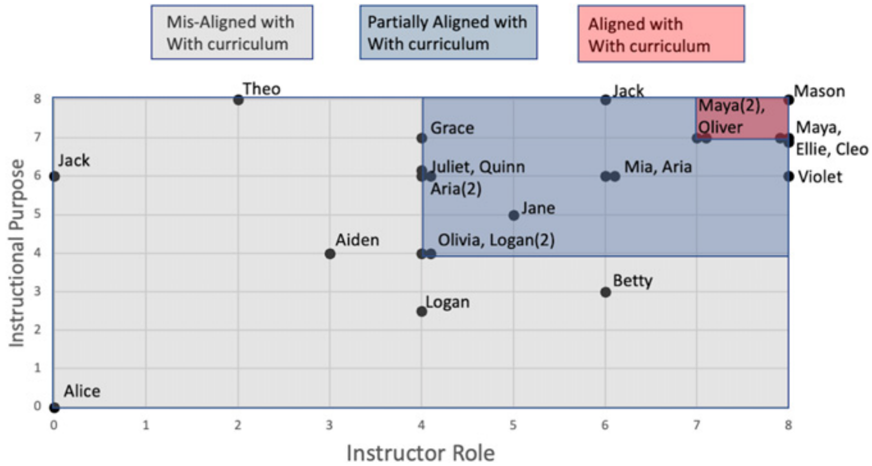

FIGURE 1. TA curricular implementation. Composite scores for each dimension are plotted for each TA as described in the *Materials and Methods*. The *x*-axis shows TA scores along the instructor role dimension, with a score of "0" indicating a teacher-centered role and a score of" "8" indicating a student-centered role. The *y*-axis shows TAs scores along the instructional purpose dimension, with a score of "0" indicating a non-practice-focus purpose and a score of "8" indicating a practice-focus purpose. TAs who taught for multiple semesters have two teaching orientation scores, the second labeled with (2).

When applying our coding guide to this episode, we considered both the in-class episode and the interview reflection. This episode was coded as "practice focus" for *Instructional Purpose* because it was clear that Ellie's actions were directed at furthering sense-making for the practice of model revision. For *Instructor Role*, this episode was coded as "student-centered" because Ellie remained focused on the students' ideas and promoting their engagement in the sense-making process. Overall, the instruction in this episode was well-aligned with the goals of the curriculum.

TAs' Curricular Implementation Varied across Both the Instructional Purpose and Instructor Role. To reveal the variation in TAs' implementation of the science practice–based curriculum, we applied our qualitative coding guide to stimulated-recall interviews ($n = 23$ interviews, four coded instances per interview). Each instance was given a score for *Instructional Purpose* and *Instructor Role*. Each TA's total score for each dimension was plotted on an *X-Y* axis, see Figure 1. Note that TAs who participated in two semesters were given a score for each semester.

TAs in our study varied widely across these two dimensions (Figure 1). We observed that several TAs' implementation was well aligned with the curricular design, demonstrating a student-centered *Instructor Role* and a practice-focused *Instructional Purpose* (Mason, Maya, Ellie, Cleo, and Oliver). This is notable, given that each of these TAs was enacting the curriculum for the first time. A similar number of TAs' implementation was misaligned with the curricular design, meaning that more than half of the time they demonstrated a teacher-centered *Instructional Role* and/or a non-practice-focused *Instructional Purpose* (typically, content or task-focused). These TAs (Alice, Jack, Theo, Aiden, Logan, and Betty) exhibited varied forms of curricular enactment. Most commonly, TA implementation was partially aligned with the curriculum (Grace, Juliet, Quinn, Jane, Olivia, Logan, Aria, Ellie, and Mia). These TAs often switched between different *Instructor Roles* and *Instructional Purposes* for diverse reasons. In the sections that follow, we explore the enactments that were misaligned or partially aligned with the curriculum. We do so because our overarching goal for this study was to understand variation in science practice–based instruction.

TAs' Enactment Could Be Misaligned with the Science Practice–based Curriculum in Different Ways. Although most TAs enacted the curriculum in ways that were at least partially aligned with the design of the science practice–based curriculum, it is informative to first consider the different ways in which *significant* misalignments occurred.

Alice is the most striking example and her enactment could be described as attempting to use a traditional teaching approach to direct her students towards scientific concepts. Her dialog with students often utilized authoritative patterns (i.e. Initial-Respond-Evaluate). Additionally, she often oversimplified the problem space because of her desire for her students to arrive at a specific idea, which in her view was needed to successfully do the task. For example, when students were asked to revise their biological models using their collected data, she told her class:

> *"One important thing to consider is, remember at the beginning of class when I talked about our learning objectives were to think about proteins? So, you're making your model. Technically, I wouldn't say it's sufficient to say that [species] A breaks down something in colominic acid. What in [species] A breaks it down? Like what type of molecule do you think? Do you think it's like DNA? Hint, hint, wink, wink. It's not. But like, like that…"* – Alice

Betty, by contrast, took on a student-centered *Instructor Role*, demonstrating her interest in encouraging her students. For example, in her interview, she explained her rationale for how she helped students design experiments to test their model:

> *"[I want them to know] if your experiment doesn't go exactly the way you planned, it's fine, don't stress. A lot of them were really worked up [the first week]…I just want to show them, like hey it's cool. Science is fluid. You are never gonna be penalized for not carrying out your idea perfectly."* – Betty

However, Betty's *Instructional Purpose* was often misaligned with a science practice–based approach. She seemed to have little interest in engaging students in science practices finding ways to simplify classroom tasks for her students and for herself. For example, when explaining how she guided students to form a hypothesis, she stated:

> *"[I am] just trying to, I guess, simplify everything, so that like I am not lost and also they can complete the task in a way that I think is the easiest for them…"* -Betty

Finally, Jack and Theo were generally invested in having a science practice–focused classroom. However, because they took on a teacher-centered *Instructor Role*, they did not typically promote students' own engagement in science practices, as we discuss in the next section.

Practice-focused Instruction is Modulated by a TA's Instructor Role. Our results show that many of the TAs in our study supported their students' engagement with science practices. Sixteen of the observed curricular enactments had a score of 6 or higher for *Instructional Purpose,* suggesting that when supporting students in these modeling tasks they were focused on science practices the majority of the time. However, TAs had different interpretations about who should be participating in the science practice. Specifically, while some TAs promoted student engagement in scientific practices (a student-centered *Instructor Role*) other TAs positioned themselves as the ones conducting the practices (a teacher-centered *Instructor Role*). For example, Maya sought to engage students in science practice. Here she reflected on supporting a group of students in designing their own experiment:

> *"So I remember my intentions were- I started off with the hypothesis, just to orient them and myself, it's like a two-part thing. . .[the group] mention a lot stuff, like a lot of staining, a lot of colominic acid breaker tests, and they ask me do you think that that's good enough? Or do you think I need to do anything after the colominic acid breaker test? And I don't want to answer because it is their experiment so instead of saying yes or no I kind of just ask them what they think will happen from their results and my intentions behind that are to get them to see what they think would happen and if they need anything else to answer their hypothesis."* -Maya

Maya's reflection illustrates how she worked to support her students' in doing science while assuming a student-centered *Instructor Role*. In this example, she wanted her students to design their own experiments and be able to move toward assessing for themselves what would be productive (lines 56–59).

By contrast, Theo assumed a teacher-centered *Instructor Role* as he engaged in science practices. Here we see Theo's rationale behind a moment where he helped his students interpret experimental findings for drawing their revised model:

> *"Their [results] went pretty pear-shaped, which was a bummer. And I don't think they did many controls, if any. So, it wound up being pretty inconclusive as a lot, which is great [sarcasm]. I was trying to- that was the second one I tried to gram stain and find for them. So, the first one, I found stuff for them, that one I was running too thin on time. . .So I was just trying to find something because they had found it in the other one and thought it was confounding data and I wanted them to see it wasn't necessarily, they weren't necessarily competing things at the whole big picture. So, I wanted them to get that piece of data, [but] we couldn't end up getting that, so I wanted to go through everything [all the data in the room] and make sure they knew 'how do I float this in a write up'. Cause I think they are so used to having the answer thing that they need a definitive yes/no but like if you are in a lab and you run out of a piece of data and you got to go present in group meeting tomorrow, you just got to write up what you write up, you need to test more. So, you know, I got a stain on the slide it looked like it, I couldn't find it under the scope, I got a cloudy tube, looks promising, I will try again. Like that's- I want them to understand that that's a fine answer in science, we are working on it."* -Theo

Theo's reflection illustrated his goal of reasoning about evidence. He wanted his students to consider ambiguous results (lines 64–67) and understand the nature of science (lines 69–75). Comparing Theo and Maya's reflections, there are differences in who is being positioned as doing the scientific work. Theo started off discussing how he spent time doing multiple gram stains for this group of students (lines 62–64). He explained how he really wanted that specific evidence available to the group as he wanted them to incorporate the result they thought did not matter or was irrelevant (lines 64–67). Unlike Maya, Theo engaged in doing science practice for his students, in this case, collecting results. He seemed to be driven to build an accurate explanation based on all the evidence he, the instructor, knew existed. Both TAs focused on building evidence-based explanations but differed in who was positioned as the epistemic agent.

Fluctuations in a TA's Instructor Role and Instructional Purpose are Often Cued by Interactions with Students. As we mentioned previously, the majority of TAs' enactments were partially aligned with the curriculum. While some TAs changed their approach for different instances or tasks, others took on different *Instructor Roles* or *Instructional Purposes* within a single student interaction. Through examination of multiple TAs' rationale for multiple of these cases, we found two emergent themes: 1) TAs move toward a teacher-centered *Instructor Role* in response to perceived student struggle and 2) TAs move toward a non-practice-centered *Instructional Purpose* in response to students' expression of ideas evaluated by the TA to be incorrect. Next, we exemplify and unpack each of these claims.

TAs Move Toward a Teacher-Centered Instructor Role in Response to Perceived Student Struggle. In the following example, we will illustrate the way TAs commonly took on both *Instructor Roles* within a single interaction with a group of students. Here, Quinn begins by eliciting students' ideas for their proposed experiment (lines 76–90). Her initial approach is focused on understanding and valuing her students' ideas. Then in line 91, she begins to take on a more teacher-centered role.

76 **Quinn:** How's it going over here?
77 **Student 1:** [They have an idea]
78 **Quinn:** Yeah? What is it?
79 **Student 1:** [They think bacteria species A transfers a gene to species E]
80 **Quinn:** That's why [species] E is able to survive?
81 **Student 1:** [Agree]
82 **Quinn:** Cool. Do you guys have ideas for how to test that? Or are you still working
83 through that part?
84 **Student 1:** [They are working on it]
85 **Quinn:** Okay.
86 **Student 2:** [Ask if bacteria will look different if swapped genes]
87 **Quinn:** For gene transfer you wouldn't see any differences. So how could you- it is
88 testable. so how could you think of using those that you have to test-
89 **Student 2:** [Propose looking at medium environments, but they are unsure if a gene would be
90 released. They ask for reassurance that they can test their idea] . . .
91 **Quinn:** Yes, so that is testable. So you guys are on the right track when you want to
92 use [species] E that was isolated from [species] A and E, what would that [species] E
93 have?
94 **Student 2:** [Maybe different genes (sound unsure)] . . .
95 **Quinn:** So could you test that? Test for the presence of those survivor genes?
96 **Student 2:** (pause). . . [Ask what surviving genes are]
97 **Quinn:** Yeah so your guy's hypothesis, the way that is sounds to me, is that you think
98 [species] A gives [species] E a gene that allows it to survive right? [students agree]
99 So if [species] E, if you isolate [species] E from that environment should it have those
100 genes?
101 **Students 1 and 2:** [Yes]
102 **Quinn:** Okay where could you put that to test if it has those genes?
103 **Student 2:** . . . [Put in new media to see if species E can survive after being with species A]
104 **Quinn:** Yeah. Right, cause what could that show you?
105 **Student 2:** [Resistance]
106 **Quinn:** Yeah so what media would you put it in?
107 **Student 2:** . . . [They propose using medium #2. Ask if this would be enough to prove their
108 hypothesis].
109 **Quinn:** Does that make sense? So walk me through your hypothesis and your steps
110 cause you guys are close- yeah. . .

Despite her initial student-centered approach to this interaction, around line 91 Quinn begins a line of questioning that progressively becomes more authoritative. Eventually, her questions are closed-ended, seeking specific, single-answer responses, which Quinn verbally evaluates.

This type of "switch" between roles was common across TAs in our sample. Exploration, of similar examples provided some evidence for why TAs may have exhibited this behavior. One reason we saw TAs "switch" roles was in reaction to seeing their students being visibly lost, frustrated, or uncomfortable. Grace's interview provided a well-articulated example of this kind of rationale. Here we show her reflection on a clip where she switched to a teacher-centered *Instructor Role* in the middle of a student interaction:

> *"So I definitely did not go up to them with the idea that I would be like 'if you take [species] A out and put [species] E in it will test your hypothesis.' Normally I don't like to do that, but walking up to this group this is one that was really struggling and just totally overwhelmed, they didn't really understand what was available. . .So right off the bat I kind of knew they were struggling quite a bit and they are one of my higher achieving groups in general too, I think they were just a little bit overwhelmed, but they really like to get the right answer and I think that was putting some pressure on them to choose an experiment that is really going to work. So walking up to them I kind of wanted to make them feel like it was okay- like you don't always need to get the right answer but at the same time you need to have something to talk about in your lab report . . ."* -Grace

Grace recognized that by the end of the episode, she had ultimately told her students what experiment they should use to test their ideas. Her rationale for this choice was due to her reaction to the group struggling and being overwhelmed by the task itself (lines 115–118). This kind of reasoning was commonly used by TAs as a part of their rationale.

TAs Move Toward a Non-Practice-Focused Instructional Purpose in Response to Students' Expression of Ideas Evaluated by the TA to be Incorrect. Our results showed that some of our TAs prioritized biology content learning goals. Often TAs had specific ideas or "right" answers they wanted students to arrive at and were often seen to switch their *Instructional Purpose* in order to transmit these specific ideas. Here, it is important to remember that the AIM-Bio curriculum was designed to support students in learning biology concepts and information through their participation in science practices. The curricular focus is shifted away from *all* students' reaching the same understanding of specific content knowledge objectives; students are expected to achieve diverse content learning outcomes (Hester *et al.*, 2018; Guy-Gaytán *et al.*, 2019). In contrast to the intended curricular goals, TAs were often found correcting students' understanding of biological concepts and moving students toward specific ideas or "right" answers.

The influence of a non-practice-focused *Instructional Purpose* was common among TAs whose enactment was partially aligned with the curriculum. An examination of TA's interviews provided insight into TA's rationale for this misalignment. For example, Logan explained why he used authoritative dialog (IRE) to get his students to think about the idea of bacteria transferring DNA:

> *"They had- there were two weird things about their model, it was mostly pretty good. They had [species] E and [species] A giving each other a different protein. . . And I wanted them to get away from the idea of them transferring proteins, I mean it's entirely possible it does happen but from an evolutionary biologist perspective it doesn't really make much sense why you would make a protein to give it away. I was hoping that would be a really fast conversation, but it wasn't necessarily the quickest. . .I was hoping it would be like 'oh yeah, no, protein is made from DNA, it makes more sense to give them the instructions instead of giving the finished product.'"* -Logan

Logan's response illustrated his rationale for assuming a teacher-centered *Instructor Role* was to correct his students' ideas about biology (lines 124–126). Within this episode, Logan's *Instructional Purpose* changed from supporting his students in developing their ideas through modeling to directing them to appropriate biological ideas (despite the fact that from our perspective, the student's ideas were biologically plausible based on what they currently knew).

Interestingly, Logan was one of the few TAs' who explicitly recognized a tension between his actions and a science practice–based approach. In his second semester teaching AIM-Bio, Logan reflected on an interaction in which he used authoritative dialog (IRE) with a different group of students to transmit information about enzymes:

> *"Uh, I remember it was a little disheartening because I felt like I kept on having to resort more to 'teaching' instead of actually like helping them come up with their own idea . . . if they knew what enzymes did then we could have cut out like 5 minutes of that, I'm sure they have learned about it before, I mean most of my students are juniors so I was like hopefully we can get this enzyme idea out there and then (pause). But I remember being a little disheartened that they- that I had to do a lot of- a lot more teaching than I wanted to do with them . . . I am worried, a lot this semester, of leading people in one direction. I don't know if I am doing it out of frustration or just falling back to things that I know fairly well or what. But I definitely feel like I am doing that more this semester and it's entirely possible I did that with this group."* -Logan

From his reflection, Logan stated that he had not wanted to "resort" to using IRE to "teach" his students about enzymes (lines 132–134). He was also worried about leading students toward specific ideas and not giving them opportunities to come up with their own (lines 137–139). Interestingly, Logan was unsure why he was leading his students to certain ideas. He speculated one possible reason as falling back on ways of teaching he was more familiar with, from previous experiences teaching a traditional laboratory curriculum (lines 138–139). However, it seems that he had not yet fully articulated for himself why it was important to him to lead his students toward specific ideas.

We see Logan's case as preliminary evidence for the potential *learning* TAs may experience through science practice–based teaching. In the above example, which was from Logan's second semester teaching the science practice–based curriculum, he seemed to recognize how his own specific actions as a teacher could delegitimize students' epistemic agency. We also see that Logan's score for *Instructional Purposes* moved slightly toward a focus on science practices from the first to second semester. Taken together, our data suggest that Logan may have begun to change his assumptions about the function of content-based learning within a science practice–based curriculum. In the next section, we explore an in-depth case of TA learning about science practice–based instruction.

Research Question 2: In What Ways can TAs Learn to Navigate Science Practice–based Teaching Over Time?

Along with understanding the teaching variation of our group of TAs as they navigated science practice-based instruction, we wanted to also investigate the ways they are *learning* to teach. As described in the *Materials and Methods*, we chose one TA, Aria, to take an in-depth look at how she learned to teach science practices over 1 year (two semesters of instruction). Aria was an undergraduate TA who had no previous experience teaching or in research.

We wanted to first establish the ways Aria supported science practice–based instruction. We examined her teaching intentions and noticed that Aria intended to support her students to engage with science practices in several ways across her two semesters of instruction. Based on our previously developed coding guide for instructor intentions (Cooper *et al.*, 2022), we found that Aria commonly intended to *Build a Supportive Classroom Culture* where she wanted to encourage her students to work collaboratively within and across their groups. In the model revision task specifically, Aria wanted to use this intention to support her students in sharing experimental data. Additionally, we noticed Aria commonly had the intention, *Check Alignment of Model and Data.* This intention was articulated in different ways by Aria depending on the task. In the experimental design task, she wanted to support her students in designing experiments that tested their proposed hypothesis. Alternatively, in the model revision task, she wanted to support her students in connecting their own experimental data, or other groups' data, to their model drawings. Analysis of Aria's intentions shed light on how she learned to teach science practice–based instruction. Specifically, we saw a shift in how she articulated her understanding of science practices over time (to be further discussed in the following sections). A full list of Aria's instructor intention findings can be found in Supplemental Table S3.

Next, we looked at how Aria carried out science practice–based instruction with her students, again, using our previously developed coding guide (Cooper *et al.*, 2022). Across the modeling and experimental design tasks, we found Aria commonly worked to make her students feel comfortable to participate by encouraging their tentative ideas (Encourage Emerging Ideas). Specifically in the tasks where students are asked to draw a model explanation, we noticed that Aria spent her time helping her students explain by encouraging them to generate ideas and fully explain their ideas mechanistically (Focus on Explanations). We also noticed Aria used practices that were specific to each task. For example, in the experimental design task, she commonly worked to support her students in understanding the different experimental tools available (Support Understanding of Tools). Additionally, in the model revision task, she commonly focused on supporting her 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). Overall, Aria prioritized supporting her students in the different science practices that were relevant to the AIM-Bio curriculum (Hester *et al.*, 2018; Cooper *et al.*, 2022). A full list of Aria's instructor supports can be found in Supplemental Tables S7 and S8.

After we had established that Aria intended to and did use science practice–based instruction, we wanted to look at her *Instructional Purpose* and *Instructor Role* across all four of her interviews. We found that Aria's *Instructional Purpose* was generally practice-focused across the year, with some instances of non-practice-focused instruction. Aria's *Instructor Role* was found to be a combination of both student-centered and teacher-centered teaching. Aria used this combined role of teaching across all her interviews, except for her final interview where she demonstrated almost exclusively student-centered teaching. Aria was similar to her peers in the ways that she held dual purposes and roles (Figure 1).

Though we did see small shifts in Aria's *Instructional Purpose* and *Instructor Role* scores over time, these findings did not fully capture the ways we saw her learning to teach science practice–based instruction based on our interview analysis. In our full analysis of Aria's case, which we will reveal next, we found multiple ways that she changed her teaching approach over time. We noticed that her *Instructional Purpose* became more refined and developed. Specifically, she moved away from goals that centered on the classroom task or aspects of classroom management. We noticed that she articulated student engagement with science practices differently, drawing from her developing pedagogical content knowledge (PCK). PCK considers the ways instructors use their knowledge of how students learn particular content and skills to inform how they teach (Carlson and Daehler, 2019). In Aria's case, we observed her developing PCK about how her students thought and learned about science practices. We also found her *Instructor Role* to change over the course of the year. Specifically, we observed that Aria became more reflective about her own teaching, began to recognize aspects of her teaching approach that were problematic, and began developing a constructivist framework for how people learn. In the following sections, we will use our *Instructional Purpose* and *Instructor Role* conceptual framework to guide our presentation of her learning. We will present each of Aria's semesters in sequence so that the reader can track changes in her thinking over the course of the academic year.

Semester 1: Aria Focused on Leading Her Students Toward Specific Ideas that Supported their Successful Completion of Science Practice–based Tasks. Across her first two interviews (semester 1), we noticed that Aria was very willing to express her reflections about her own teaching which provided us with novel insight into the reasoning behind her actions. Our case analysis revealed that Aria's *Instructional Purpose* was generally practice-focused across her first semester, where she focused on supporting her students to complete the scientific practice task they were assigned. For example, in her first interview, she discussed her goals for her students as they engaged in the practice of revising models:

> 142 *". . .I just wanted everyone to be on the same page, and I wanted them to understand*
> 143 *it, especially because they have a write-up this week. . .So I think when I was doing,*
> 144 *like going over the models, was like, how do you know this is your model? And I*
> 145 *wanted them also to think about that because in the first write-up, a lot of them, when*
> 146 *they were explaining the revised, didn't include their data or observations, and they*
> 147 *got points off. Like, okay, how do you know this is the mechanism? What tells you*
> 148 *that?"*

Aria's goal for her students in the model revision task was to set them up to successfully write their lab write-up at the end of the unit. She recognized that they needed to engage with the science practice itself to be successful in this task, such as having experimental evidence to support claims in their models. Additionally, her goals during her first semester often focused on general aspects of managing a classroom:

> 149 *"I want to make sure every group member was included, and they all knew what was*
> 150 *going on. I wanted to keep in mind, like, time management, because I don't want*
> 151 *[them] to overwhelm themselves with the amount of tests that they were going to run.*
> 152 *And then I think they also had to do the order form today. So, I wanted to make sure*
> 153 *that they had a clear idea of what each task was going to entail and outline it in the*
> 154 *chart."*

In this example, she aimed to help the students manage the task of experimental design. Specifically, she wanted to make sure they worked well together in their groups, that she helped them consider how much time they had to carry out their experiments, and that they did the worksheet (the order form) to make sure they would have the materials they needed the following week.

During this first semester of Aria's teaching, we observed a shift in her goals during the final week of each unit. Specifically, we saw her *Instructional Purpose* shift from science practice–focused to content-focused during the last day of each unit. In the case of the first interview, which was a unit that Aria had experienced herself as a student, she focused on moving her students toward her idea of "the answer." In the next example, Aria reflected on a clip where she had asked a group of students whether they talked with another group of students about their experimental data (Make Ideas in the Room Accessible instructor support):

> *". . .And like I said, I wanted them to also include other group's data because there was very specific experiments that were really, like important. . .They're like, these are really key to what this new phenomena- like mechanism for the phenomena is. So I want to make sure they have those key points down."*

Aria's reflection revealed that she had a specific answer that she wanted her students to get to by the end of the unit. In this case, she wanted her students to collaborate because they had completed a "key experiment" that she wanted them to include to have "the mechanism" for the phenomena being investigated.

Aria had a similar, content-driven goal in her second interview as well. Her experience with the later unit was unique in that she had not experienced it as a student before teaching it. She discussed the challenges she faced supporting her students when she did not know what to expect. Specifically, she found herself focusing on understanding the phenomena for herself while teaching. The next example shows Aria's reflection on her teaching approach in this final week of the later unit:

> *". . .the last week. I was like so excited about the results that I feel like I was shifting away from, like letting them interpret. And like, you know, [using] leading questions and [I would] think, what is their experience? I was, like, having my first experience with it too."*

Aria was excited to see her students' experimental results and reason through their data alongside them. Her reflection revealed that she felt like she was not supporting her students in science practices (through "leading questions") as she was more focused on making sense of the phenomena for herself. Similar to her first interview, we noticed in her latter interview Aria was asking students to consider specific pieces of data that were often not connected to the students' stated ideas.

In the next example, Aria reflected on an episode where she pushed her students to consider another group's data (Make Ideas in the Room Accessible instructor support) and draw a mechanistic explanation (Focus on Explanations instructor support). She was asked by the interviewer why she asked her students to consider multiple, specific aspects of how *Chlamydomonas reinhardtii* swim:

> *"Yeah, I think partially because my personal hypothesis is that the reflective layer directs it somewhat. [pause] So, I mean maybe that was influenced by it. . ."*

In the latter unit, Aria actively worked with her students' experimental data to build her own hypothesis for what she believed "the answer" to the phenomena was. As with the first unit, we observed moments where she used leading questions to direct her students toward her own personal model. Overall, we found that Aria was motivated to support her students to successfully complete the science practice tasks and move them toward her perceived conception of an "ideal answer."

Aria's *Instructor Role* during her first semester of teaching was both teacher-centered and student-centered. Aria was student-centered in that she listened and was impressed by her students' creative ideas. We observed her tracking the different ideas across the multi-week units and asking her students follow-up questions to make sure she understood their thinking. Our next example shows Aria's reflection on an interaction where she worked closely with a group to further develop their idea and test:

> *". . . by the end [of the conversation], they were able to say that their hypothesis was that [species] A breaks down the acid, neutralizes the solution, [and] makes it safe for [species] E as well. And they also wanted to go a step further, it wasn't a part of their hypothesis, but they wanted to see if [species] E was maybe changed or altered by [species] A for it to be able to survive. . . I'm not necessarily against it because I feel like it is nice for them to have a hypothesis and some experiments that test it, but they are like 'I'm also curious about this [other] thing so I want to see this'- so I didn't discourage that."*

Her reflection highlights how she wanted her students to have agency over their ideas and experimental designs. Aria first worked to help the group refine their hypothesis (Focus on Explanations instructor support) and design an experiment to test this idea. However, she recognized that they had other ideas beyond their hypothesis that they also wanted to test. Her reflection revealed that she encouraged her students' curiosity and let them explore multiple ideas. In addition to her student-centered role, Aria was also observed using teaching-centered strategies where she led students to specific ideas. The next example shows Aria interacting with a group of her students during the model revision task in her second interview. Earlier in the episode, Aria used IRE to support her students in interpreting different experimental results. This episode begins with Aria using chalk to draw out a model of the phenomena for the students:

Aria: . . .Yeah. Let me pull up some chalk. I love chalk. Okay. I have a quick question. So I'm going to say, okay, this is chlamy [*drawing with chalk*]. And this is our eyespot. So this is our reflective layer. These are our proteins. So I'm going to pretend to do something. Guys, come take a peek. I have a question. So we have this reflective layer. What happens to light that comes from here?
Student 1: [It reflect the color of the layer]
Aria: Okay, so it's reflected here. What about light that comes from this direction?
Student 2: [The layer surrounds the entire thing]
Aria: So it reflects it back?
Student 2: [Agree]
Aria: Yeah? So what happens to a Chlamy that now doesn't have it? What happens to light hitting it from every single direction?
Student 3: [It moves through]
Aria: It goes through. So maybe you guys are putting such high-intensity light at it right here. What's going to happen when it doesn't have this layer?
Multiple Students: [It goes everywhere]
Aria: Possibly, yeah.
Student 4: [It moves but doesn't know where to go (confused noise)]
Aria: So maybe this tells it where the lights coming from?

Aria used chalk to draw a model of the system to reason with this group through the mechanism of the phenomena. We can see her using IRE as a strategy to lead her students through her own personal model of the mechanism of the system. In her reflection on this moment, Aria discussed how she felt like the students were unable to make sense of their data and needed additional support. As we saw from our previous analysis of the other TAs, Aria also seems to be using the teacher-centered strategy IRE to ease any uncomfortableness or confusion her students were experiencing. One of her reflections from her first interview gives us additional insight into her views on "telling" versus "leading" her students:

"Yeah. So I mean, I almost- after, I thought maybe I gave them too much information by giving them like, 'Oh, what if you put the acid in ATTC3 [medium]?' I was like maybe that's giving them too much information. So, I actually had that conversation with like two more groups after that and I led them to [it]. I was like, 'Okay, what does it grow in? Okay, so since we already know it can grow on this, if you'- I don't think I worded it the same way. . .by the end of lab, I was like, okay, this is the best way to lead them to it rather than saying it. I think this was the first group I talked to about it."

Aria believed that leading her students in specific directions, using IRE as a strategy, was different than simply "telling" them what to do. This perspective provided insight into Aria's combined use of both student-centered and teacher-centered strategies, as she viewed teacher-centered approaches as being essential to supporting her students. Across her first two interviews, we noticed Aria being reflective about her own teaching, often questioning her own approach. However, she was often seen resolving any tension she felt in the moment during this first semester.

In Aria's first semester of teaching, we observed her prioritizing supporting her students in science practices (practice-focused *Instructional Purpose*). However, we did observe moments where she moved into a content-focused purpose, specifically in the final week of each unit. During these weeks, her purpose also shifted to prioritize teacher-centered approaches, like IRE (teacher-centered *Instructor Role*).

As we move to Aria's second semester of instruction, we will describe the aspects of her teaching that we observed to change. It is important to note that some aspects of Aria's teaching do not change, for example, Aria's shift toward a content-focused purpose during the final week of the unit continues into her second semester of teaching (third interview). However, in our final observation of her teaching (fourth interview) we observed more dramatic shifts in her teaching, including her retaining her practice-focused purpose during the final week of the unit (not previously observed in her earlier interviews). We will next present the ways Aria changed from her first semester of instruction.

Semester 2: Aria Began Developing a Constructivist View of Learning and Prioritized her Students' Engagement in Science as a Practice. While Aria began with an emphasis on supporting science practices, we saw learning and growth in how she carried out a practice-focused *Instructional Purpose* in her second semester. Specifically, her goals moved away from focusing on aspects of classroom management to instead focused on engagement with science practices:

> *". . .I think they usually get a lot of information with the tools and I like to go through it with them. And I like when they get kind of-- they take ownership. . . We're like, 'Okay, take out something that you're interested in studying and then figure out with a tool, can [you] actually experiment with that.'"*

Aria's task goals in this example centered on supporting her students in designing experiments that aligned with their hypothesis (lines 202–203). Her task intentions for experimental design have greatly shifted from this same timepoint in her first semester where she only expressed classroom management goals (lines 149–154).

We also saw evidence for Aria's development of PCK. Her task intentions shifted from being classroom task-focused to focusing on her students' productive engagement in science practices. Importantly, Aria's motivation for this shift was informed by how she observed her students thinking and engaging with model revision over time:

> *"I think the biggest challenge I've seen students face is implementing everyone's data or addressing weird results. . .I really want to have students have a reference for how to address weird results. So, I put, like, a little flowchart on the board, and I said, okay, if it's a weird result, do you have evidence that supports this, or do you have evidence that goes against this? And if you have evidence that supports this, then you kind of need to consider revising your initial hypothesis or idea based on this weird result that you weren't expecting. But if you have evidence against this, another group didn't replicate this weird result, then you have to think about, maybe experimental error or something that went wrong. And I don't like when students immediately go to experimental error when it's something they're not expecting, they're like, 'no, my hypothesis is absolutely right'. . ."*

Aria noticed that her students were often only incorporating data that was "convenient" and supported their ideas (lines 212–214). As she noticed this student challenge limited their ability to engage in the practice productively, she decided to implement a new pedagogical strategy in response (line 206). This reflection highlights some of the PCK she developed about how her students thought about and learned about science practices (i.e., model revision). Here, we saw Aria develop knowledge about instructional strategies (i.e., flowchart on the board). Her reflection revealed how she anticipated a challenge her students would encounter when revising models (i.e., including contradictory results) and used this knowledge to implement an instructional strategy to address this anticipated challenge. Specially, she tailored her instructional strategy to the specific science practice–specific challenge she knew her students would encounter. This example is starkly contrasted with her response to the same question from the previous semester (lines 142–148), where she had a task-based intention focused on writing the end-of-the-unit lab report.

Consistent with what we observed in the first semester, we noticed Aria continued to implement a combination *Instructor Role*. Aria strived to support her students in a student-centered way, specifically by providing them with agency to explore their own ideas and build their own explanations. She reflected on this challenge in her third interview:

> *"I don't know if this is really a challenge, but something I have to remind myself constantly of, is that even though we kind of know what happens, it's okay if students don't get to that. I was just going through the revised models last night, like, writing comments, and they all still have really diverse ideas, which is good because I never want to push them too much to like- what might have actually happened. So, I think I was actually constantly reminding myself that if they put an idea out there, that's a great idea, regardless of what actually happened. So, yeah."*

Aria recognized that the goal of the curriculum was for her students to develop and test their own ideas. She also recognized that her students did not all need to get to the same endpoint at the end of the unit or to her perception of the "right answer."

Although Aria had the goal of moving away from a content focus in the final week of the unit, we observed her teaching to still include many elements of teacher-centered instruction at this time point (around the time of the third interview). In her fourth interview, we saw evidence of her continued reflection on her *Instructor Role*. Specifically, she more critically reflected on her teaching choices after she heard herself pushing a group of students toward an idea that was not their own (Focus on Explanations instructor support):

> **Aria:** *". . .I like their idea about ATP. I like how they're kind of connecting multiple things. I guess my intention is I have my own agenda. About what we want to look at [laughter]. I don't even realize it until we come in here [to the interview] [laughter].*
> **Interviewer:** *Can you talk more about your choice to push them on the role of the carotenoid layer versus plasma membrane proteins?*
> **Aria:** *I do like to go more into detail about their model and ask about different components of it. I think in hindsight, I should have asked more about ATP and its role because they were kind of leaning towards that. Like I said, I realize I have an agenda, next semester I'm going to get better [laughter], I'm not going to."*

In this example, Aria reflected on the fact that she noticed that she had her "own agenda" or moments where she pushed her students to ideas that were unrelated to their own. Her reflection revealed that she viewed this as problematic and something she did not want to do going forward. Aria wanted to support her students in exploring their own ideas and was surprised to find moments where she deviated from this goal.

Aria's fourth interview also revealed the ways she began to develop a constructivist view of learning. In the next example, we will see an interaction where Aria used the student-centered teaching approach of "walking away" to leave the group to work on a task themselves. Students in this example were engaging in the experimental design task investigating how *Chlamydomonas reinhardtii* organisms swam in response to light (phototaxis):

> **Aria:** How's it going?
> **Student:** [worried everyone picked the tool they want to use]
> **Aria:** Colors? Not everybody.
> **Student:** [ask if colored filters go on the light boxes]
> **Aria:** They go with all of them [all tools].
> **Student:** [Confirming they can use colored filters with any tool]
> **Aria:** Yeah.
> **Student:** [want to do the light box assay as they are curious how phototaxis might be affected]
> **Aria:** Hmhm. So you're going to do all the colors and put-- what kind of strains are you putting in it?
> **Student:** [wild type strain]
> **Aria:** Just wild type?
> **Student:** [keep it consistent to use as a control]
> **Aria:** Yeah, I like it.
> **Student:** [Okay]
> **Aria:** So what is your hypothesis?
> **Student:** [Chlamy phototaxis will be affected by different wavelengths]
> **Aria:** Why is that?
> **Student:** [just think that]
> **Aria:** Okay. I think part of your hypothesis should be a little bit of an explanation. Right.
> **Student:** [Okay]
> **Aria:** So why would different wavelengths affect [it] differently? [pause] Think about it. I will be back.

In this episode, Aria provided her students with additional information about the available tools (Support Understanding of Tools instructor support; line 235) and asked them clarifying questions about their proposed experimental design (lines 240–241, 243). After taking the time to understand their experiment, Aria asked the group about their hypothesis (line 247). She then left the group with the task of generating the "why" behind their hypothesis (Focus on Explanations instructor support; lines 251–255). After listening to this interaction in the interview, Aria reflected on her intentions:

> 256 *". . .their hypothesis was a little bit vague. They were like, okay, there's going to be*
> 257 *an issue or something changed by the different colors, and I was like, "Well, how?"*
> 258 *and she was like, "That's what I think. That's just what I think." So, I wanted to kind of*
> 259 *let them think through it because sometimes it's beneficial for you to walk them*
> 260 *through it but this time it's pretty straightforward, in my opinion, for how different*
> 261 *colors can affect it differently. So, I want them to think through it themselves, yeah."*

Aria's reflection highlighted how she worked to support her students to engage in the science practice of designing testable experiments. She recognized that her students needed to have testable mechanisms in their hypothesis, pushing this group to engage in this part of the practice. Aria also reflected on the fact that she wanted her students to come up with the mechanism of their hypothesis by themselves. She was next asked to elaborate on her choice to leave the group to work on refining their hypothesis without her:

> 262 *"I think if I get too involved, sometimes-- [exasperated sigh] I can tell if I get too*
> 263 *involved. I want them to be able to work through things on their own, especially at*
> 264 *this point in the semester . . . There was this one student-- I was walking through the*
> 265 *results with them and helping them interpret it, and then we got through this whole*
> 266 *explanation. I was like, "Okay, cool," and then I come back a few minutes later. He's*
> 267 *like, "What did we say again? I'm trying to type it out," and he had like no idea. So*
> 268 *then I felt like, okay, maybe I almost did too much if they can't even say it in their*
> 269 *own words. So that's why I think for certain things that are straightforward, I can just*
> 270 *walk away and come back."*

Aria recognized that she can "get too involved" and "do too much" from the evidence she had collected from her own teaching. Aria's reflection here revealed the ways that she has begun to develop a constructivist framework for how her students learn. Specifically, she recognized that she needs to create opportunities for her students to do the work and engage in the practices themselves in order to learn. This change in her learning was contrasted with her first semester where she would have been seen staying to ease any confusion or frustration that she perceived her students might be feeling from not knowing the answer or what to do.

Across these two semesters, we saw evidence of the ways Aria learned to implement science practice-based instruction. Her *Instructional Purpose* shifted away from completing classroom tasks or aspects of classroom management (lines 142–148 and 149–154). Instead, she developed goals centered on her students' productive engagement with science practices (lines 200–203 and 204–214). This shift seemed to be driven by her developed pedagogical content knowledge through teaching the first semester (lines 204–214). Additionally, Aria's *Instructor Role* shifted to be more student-centered by the end of the year. Aria was more reflective about her own teaching and wanted her students to drive the direction of their own inquiries, regardless of the "endpoint" they got to (lines 215–221). By her final interview, Aria recognized aspects of her teaching that she viewed as problematic (lines 222–230) and began developing a constructivist framework for how her students learn (lines 256–261 and 262–270).

DISCUSSION

Science practice–based laboratory curricula can provide undergraduate students with opportunities to participate in science. If biology educators want to adopt a "science-as-practice" approach for our students (Lehrer and Schauble, 2006), we must better understand how different instructors enact this type of curriculum. The current study uncovers how laboratory TAs engage with students in a model-based inquiry curriculum, specifically within tasks designed to promote the scientific practices of experimental design and model revision. Findings showed that a TA's instructional purpose and role influenced how they supported students in these practices. In some cases, instructors had other purposes for their interactions with students that competed with "science practices," such as wanting students to learn scientifically correct information or feel comfortable in the class. These findings aligned with what has been previously hypothesized as a "models of" perspective, in which instructors are focused more on knowledge products (i.e., final form models) than the process of modeling (Gouvea and Passmore, 2017). Additionally, taking a "models for" perspective requires that instructors remain willing to foster students' own engagement in modeling practice, allowing them to act as epistemic agents. Our study found some TAs who consistently fostered this type of engagement for students and other TAs who consistently attempted to maintain control of students' reasoning rather than allowing students to fully participate in science practices. Importantly, the majority of TAs in our study took on **both** of these instructor roles at different times, primarily in response to cues from their interactions with students.

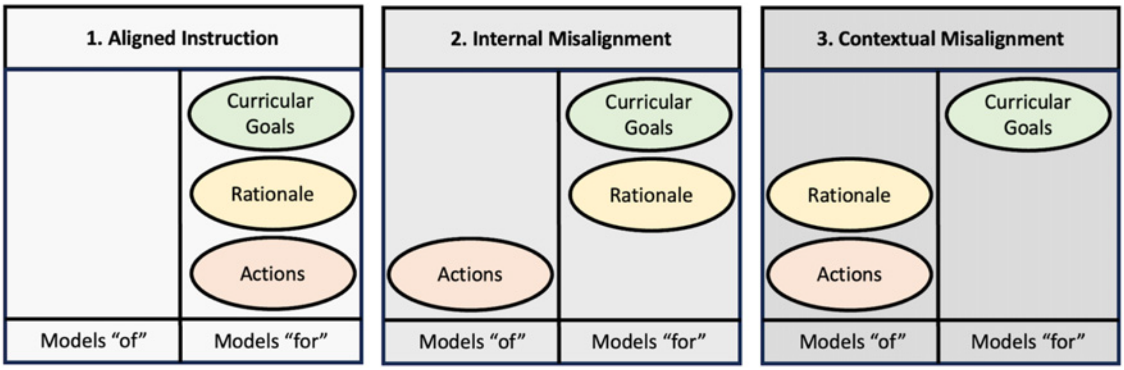

FIGURE 2. Model for variation in curricular enactment. Each box represents three different forms of curricular enactment that TAs fluidly moved between: aligned instruction, internal misalignment, and contextual misalignment. Aligned instruction describes moments when instructional actions, rationale, curricular goals all aligned with science practice–based instruction goals. Internal misalignment describes how an instructor's rationale and curricular goals are aligned with science practice–based instruction, but their enacted actions are misaligned with these goals. Contextual misalignment describes the ways an instructor's actions and rationale are be misaligned with the goals of science practice–based instruction and the curricular goals.

Our investigation provided strong evidence that in most instances TAs were attempting to enact responsive instruction (Hammer *et al.*, 2012; Cooper *et al.*, 2022). Each TA audio recording had many examples of TAs having extended conversations with students during science practice–based activities. During these conversations, TAs typically attempted to elicit students' ideas and respond in some way. Stimulated recall interviews revealed in most cases that TAs were thinking carefully about what students said and how they should respond. We suggest this demonstrates that TAs were taking an important step towards responsive teaching by noticing student thinking (Sherin *et al.*, 2011). However, what TAs were able to notice within these interactions likely varied based on their level of expertise in science practice–based instruction (Gibson and Ross, 2016).

While TAs often aimed to respond to their students' thinking, their ability to flexibly do so was influenced by their *Instructional Purpose* and *Instructor Role* in that instance. Some TAs consistently responded flexibly to diverse student needs in order to promote their successful participation in science practices. Other TAs were less likely to respond in these ways, possibly due to a weaker commitment to a "science-practice" purpose or "student-centered" role or perhaps due to less understanding and comfort with science practices. Based on how TAs reflected on their own instruction, we also suggest that many of the TAs in our study were actively learning how to carry out effective, responsive instruction in this context (e.g., Logan and Aria). We posit that understanding enactment of science practice–based curricula should consider the different aspects of learning to flexibly respond to individual student thinking.

Model for Variation in Curricular Enactment

Our goal was to understand how to support TAs in carrying out a science practice–based curriculum. Because the "enacted curriculum" is dependent on the interactions between the teacher, students, and instructional materials (Ball and Cohen, 1996; Berland, 2011), it is important to investigate the diverse ways instructors engage with students within a new curriculum. However, instructors' classroom actions alone do not fully capture *why* instructors make in-the-moment instructional choices. We argue that to better understand implementation, we need to also understand how instructors' in-the-moment decision making influences the enacted curriculum. The results of our study underscore the fact that instructors do not make pedagogical decisions in a vacuum. Their views or beliefs and their teaching context contribute to their implementation choices.

Our analytical approach of investigating stimulated recall episodes for TAs along two dimensions (i.e., *Instructional Purpose* and *Instructor Role*), allowed us to explore the interplay between TAs instructor actions, rationale, and curriculum. Our findings revealed that TAs' enacted instruction can take different forms in which alignment between actions, rationale, and curricular goals varies (Figure 2). Although an individual TA may tend to use one of these forms most often, our data suggests that fluid movement between forms is common.

Our results suggest different possibilities for why TAs may enact a science practice-based curriculum in different forms. First, many of the TAs had moments where their instructional actions and rationale aligned with the goals of the curriculum (1. Aligned Instruction). We hypothesize that in these moments' TAs understood the goals of the curriculum and worked to support students in science practice–based instruction. They positioned their students as the ones conducting scientific inquiries and worked to flexibly respond to their students' different ideas. They had goals and rationale that aligned with the curriculum designers' intentions and actions (Cooper *et al.*, 2022), though the TAs varied in their depth of understanding of science practices and pedagogical approaches. TAs who commonly implemented this form of instruction (e.g., Mason, Ellie, and Maya) had some previous research experience. Based on our previous work (Cooper and Bolger, 2023), we believe research experience could be one important influencer for this form of instruction.

Second, many TAs had moments when their actions and rationale were aligned but misaligned with the goals of the curriculum (3. Contextual Misalignment). We hypothesize that in these moments TAs had coherent goals for their instruction, but these goals were not the same as what the curricular designers intended for a particular lesson. TAs who commonly implemented this form of instruction (e.g., Jack, Alice and Betty) had previous experiences teaching traditional laboratory curricula. This may have influenced their choice to use more traditional approaches (e.g., IRE) or prioritize biology content objectives. This hypothesis aligns with previous work in K-12 and undergraduate contexts that show the important influence previous classroom experience can have on instructional implementation (Crawford, 2007; Ford and Wargo, 2007; Windschitl *et al.*, 2008; Grinath and Southerland, 2019; Duffy and Cooper, 2020). Further, when TAs demonstrated contextual misalignment, we noticed that they did not seem to perceive tension with their instructional approach. We hypothesize that TAs existing beliefs, frameworks, and goals, developed in a previous context, may have influenced this form of instruction. If TAs based their in-the-moment actions on their previously developed beliefs and frameworks, they could avoid experiencing tension with the curriculum.

Third, many TAs had moments when their rationale was aligned with the goals of the curriculum, but their actions were misaligned (2. Internal Misalignment). We hypothesize that in these moments' TAs had "bought-in" to the overall goals of the curriculum, but their classroom actions undermined these goals. TAs who commonly implemented this form of instruction (e.g., Aria, Logan, and Quinn) were diverse in their prior research and teaching experiences. Due to this diversity, we pose several hypotheses to explain this form of instruction. First, TAs experiencing internal misalignment seemed to be balancing competing ideas about curricular goals and student learning. For example, TAs had competing goals to make students feel comfortable as learners or to help students engage in science practices. Because they as students were able to uniquely empathize with their students' struggles, they may have prioritized student comfort. Alternatively, TAs may hold multiple, and possibly conflicting ideas, about student learning. TAs may hold (likely implicit) ideas about learning that lie on a spectrum between transmissionist and constructivist perspectives. As their views about learning are still being developed, they are more likely to react to the specifics of the moment (i.e., student frustration) or let competing goals (e.g., content learning goals) take precedent. This can cause TAs to implement strategies (e.g., teacher-centered *Instructor Role*) that are misaligned with their ideas about learning (e.g., constructivism). Aria's case illustrates one example of how a TA's ideas about learning can move toward a constructivist perspective and how this view encouraged her to remain student-centered in moments when she may have previously reverted to teacher-centered methods. Second, TAs are tasked with teaching a curriculum that they did not develop, leading to "fidelity of implementation" tensions (O'Donnell, 2008; McNeill *et al.*, 2018; Duffy and Cooper, 2020). TAs are asked to buy-in and trust a curriculum they do not fully understand, requiring them to navigate their own uncertainty as they teach. This is a challenge that is also identified with K-12 teachers (Manz and Suaŕez, 2018) and requires teachers to release some of their control over the direction of the learning. It is important to consider that reformed curricula further exacerbate this problem as TAs have never experienced this type of curriculum as a student. Third, TAs are being asked to do more than just support student learning of science content goals. Reformed curricula, like AIM-Bio, also require TAs to support their students' engagement with different science practices. This is especially challenging as many of the TAs only have minimal experience engaging with these practices themselves. Our previous work detailed the critical role that an understanding or epistemology of science can have in supporting science practice–based instruction (Cooper and Bolger, 2023). Fourth, TAs may be uncomfortable with new pedagogical approaches needed for science practice–based instruction or have limited knowledge about these practices.

TAs are Capable Learners

TAs are uniquely positioned as learners. They are often new instructors, who are eager to learn how to teach. TAs are also science newcomers who are learning as science students and often learning to carry out their own research investigations. Their dual-learning roles as science students and new science instructors, position TAs for integrated learning about science practice–based instruction. Our study sheds light on the potential for learning in the TA population, illuminating possible mechanisms of learning about science practice–based instruction.

Aria's case illustrated one example of the ways TAs can learn to support students in science practices. Through teaching science practices over 1 year, Aria learned what a model was for (Gouvea and Passmore, 2017). Aria began with a "models of" perspective, in which her *Instructional Purpose* focused on classroom tasks and *Instructor Role* aimed to move students toward canonical or "predetermined" ideas. This perspective greatly shifted in her final semester of teaching where she prioritized her student's engagement with science practices, a "models for" perspective.

Active Engagement with Science Practices. Across her first semester, Aria prioritized her own active engagement with science practices. In weekly PD meetings, we saw Aria enthusiastically participate in different activities that asked TAs to engage with science practices. This included building their own models or designing experiments as well as analyzing experiments and data from past students. In her own classroom, Aria worked to actively track all of the different ideas and data across her classroom. In her second interview (first semester), we also saw her actively building her own evidence-based explanation for the phenomena using her student's experimental evidence (lines 159–162 and 173–191). Aria's own engagement with different science practices was likely a critical component that allowed her to construct her own understanding about the science practices themselves (Windschitl and Thompson, 2006). We hypothesize that this engagement facilitated Aria's knowledge about what models are for, why people might engage in modeling as a practice, and how people engage with models.

Role of Reflection. Throughout her interviews, we found Aria to be reflective about her students' experience and her instruction. She cared about her students and their ideas and often reflected on their different experiences and how they engaged with different science practices. Aria also reflected on her own beliefs and teaching practices which prompted her to adapt her instructional approach over time. Though there are many interpretations of "reflective teaching" or reflective approaches (Calderhead, 1989; Hatton and Smith, 1995), there is general consensus on the important role reflection has in supporting teaching practices and growth (Luft, 2001; Sherin and Han, 2004; Lotter and Miller, 2017). We specifically noticed that Aria's reflections revealed aspects of her instruction that she viewed as problematic (lines 223–231). Teacher dissatisfaction or "pedagogical discontentment" is a well-known mechanism of teacher change in the literature (Feldman, 2000; Gess-Newsome *et al.*, 2003; Southerland *et al.*, 2011). This idea arises from conceptual change theory which relies on a learner being dissatisfied with their existing ideas pushing an individual to accommodate or change their ideas (Posner *et al.*, 1982). Instructors can experience "pedagogical discontentment" when they feel their teaching actions are not meeting their goals (Feldman, 2000; Southerland *et al.*, 2017). We suggest that Aria's dissatisfaction with her own approach or "pedagogical discontentment" promoted her learning overtime.

Development of Pedagogical Content Knowledge. Aria developed knowledge of how students engage in science practices through teaching over multiple semesters. Specifically, Aria gained PCK or knowledge for teaching a competency (i.e., science practices) to her undergraduate students. Though PCK has traditionally focused on knowledge used by instructors to teach specific topics or concepts, we argue that there is also needed PCK or instructor knowledge around how students think and learn about science practices. Lee Shulman, who first introduced the construct of PCK, has discussed limitations around its original conception and how this construct needs to evolve and change to meet the current conversations (Berry *et al.*, 2015). We feel this is especially important to consider as priorities in both K-12 and undergraduate education move to emphasize science practices as an intended learning objective (American Association for Advancement of Science, 2011; National Research Council, 2012). Aria's case provides evidence that there is PCK around competencies (e.g., science practices) as well as evidence for how developing PCK supports learning in novice instructors. Aria's interview revealed that she knew that her students commonly "ignored" contradicting or challenging data when engaging in the science practice of model revision (lines 204–214) (i.e., PCK construct "knowledge of student thinking"). This knowledge allowed her to anticipate this student challenge and be able to tailor her instructionally strategy to specifically address it (i.e., PCK construct "knowledge of instructional strategies). Aria's PCK for teaching model revision relied on the ways she utilized her knowledge about how her students engaged with this practice to motivate her implemented instructional strategy. Our finding also provides further support for previous work that has also shown the development of pedagogical content knowledge in learners, especially of instructors at different levels of experience (Shulman, 1986; Hale *et al.*, 2016).

Although Aria was only a single case, we do think she shared similarities with many other TAs in the population. Like many of the TAs, Aria's did not have any previous teaching or research experience. She was a newcomer to teaching and science, developing her ideas for both through active engagement with the curriculum and her students. Aria was also similar to other TAs in that she brought in her own resources, values, and beliefs which influenced her enacted approach. In Aria's case, she brought in her nurturing orientation. She cared about her students as people and was genuinely interested in their different ideas. This resource motivated her behaviors in the classroom as we saw many instances of her tracking her students' ideas, being interested or excited about their ideas, and generally cheering on her students' success.

In addition, we see evidence to suggest that the mechanisms of learning for Aria were present for other TAs. During PD meetings, TAs engaged deeply in science practice–based activities and seemed to learn about modeling, data interpretation, and experimental design. During interviews, TAs who were experiencing internal misalignment, sometimes described dissatisfaction with their instructional approach. Finally, we found frequent evidence that TAs gained "student knowledge" through their practice over time, especially among those who taught the curriculum for multiple semesters. They often referenced their students' challenges from previous lessons as part of their rationale for instructional choices.

Practical Implications

This study joins our previous work (Cooper *et al.*, 2022; Cooper and Bolger, 2023), in unpacking aspects to consider for implementing science practice–based instruction in undergraduate classrooms. The current study highlights the ways TAs are uniquely positioned to learn about both science and teaching. We argue that PD training should provide opportunities for development in both aspects. PD should also consider the various ways TAs may enact a science practice–based curricula (Figure 2) and how to best support TAs in each of these forms. We will next speculate about how the results of this study could inform preparation of TAs for science practice–based instruction.

PD Should Scaffold TAs' Reflection on their Instruction. As discussed in the previous section, the role of reflecting on practice was a critical aspect that drove Aria's learning and is a known mechanism that supports the growth of teaching practices (Luft, 2001; Sherin and Han, 2004; Lotter and Miller, 2017). As such, PD developers should aim to create opportunities for TAs to reflect on their teaching and build a reflective teaching community. This could be accomplished by asking TAs to engage in written reflections or group discussions where they reflect on their own teaching practices from the previous week. Another approach could be to ask TAs to participate in a "video club" (Sherin and Han, 2004; van Es and Sherin, 2010). In this approach, instructors are asked to watch videos of their own classrooms and instruction with other instructors. During the video club, they have opportunities to reflect on 1) their own instruction and 2) other instructors' approaches. We predict that providing opportunities to reflect could be especially beneficial for TAs who implement instruction that is internally misaligned (Figure 2). Because TAs who implement this form of instruction understand the goals, but enact actions that are misaligned, reflection could be a powerful tool that supports these instructors to notice their own misalignments and begin to consider how change their practices.

PD should Include Opportunities for TAs to Further Build their Conceptions of Science Practice. Previous work looking at both K-12 teachers and TAs have shown that they often have variation in their understanding about the epistemic aims of science (Varelas *et al.*, 2005; Goertzen *et al.*, 2010; Sandi-Urena *et al.*, 2011). We similarly observed TAs with various depths of understanding about science practices, which informed their instructional approaches. Importantly, Aria's case illustrated how TAs could develop their own conceptions of science and support their enacted instruction. PD developers should aim to develop opportunities for TAs to practice and learn about science practices in order to develop their conceptions of the epistemic aims of science. This could be carried out by asking them to engage in science practice activities themselves during PD (e.g., designing experiments or interpreting data), beyond solely focusing to prepare to teach the next week of instruction. By engaging in science practices in PD, TAs can engage in scaffolded opportunities with support from PD facilitators where they deepen their understanding of science practices and science practice–based instruction.

PD Activities should Help TAs Build a Conception for the Overarching Goals of the Curriculum. Previous work on "fidelity of implementation" has noted the importance of instructors knowing and utilizing the goals of a curriculum as being more important than maintaining the detailed structures of a curriculum (McNeill *et al.*, 2018). In our study, when TAs implemented instruction that was contextually misaligned, their goals for instruction differed from those of the curriculum (Figure 2). This could occur when TAs did not already have an overarching understanding of the overall goals of science practice–based instruction. To foster a shared understanding of curricular goals, PD developers should consider how to provide opportunities for TAs to "buy in" to the goals of a science practice–based curricula. One approach could be to ask TAs to participate in aspects of the intended curricula as a student. PD activities could then ask students to reflect on that experience to help frame how a science practice–based approach is differs from the forms of instruction they may have previously encountered as an instructor or student.

PD should Assume that TAs will Construct their Own Understanding of How to Implement Science Practice–based Instruction. Our analysis showed that TAs in our study constructed very diverse understandings of science practice–based instruction. The stimulated recall interviews revealed how TAs were making sense of their own implementation and at times were changing their understanding of instruction (e.g., Aria). A premise of science practice–based instruction is that students have epistemic agency to construct their own meanings and interpretations (Miller *et al.*, 2018; Guy-Gaytán *et al.*, 2019). Our analysis suggests that framing instruction in this way is challenging for many TAs. Therefore, we posit that PD should aim to use a constructivist approach to TA learning. This could enhance TA learning as well as model the forms of instruction that TAs could carry out. Through this approach, PD developers should seek to elicit TAs ideas and provide opportunities for them to construct their own understanding about science practice–based instruction. This could be carried out through open-ended prompts that elicit collaborative discussions about instruction, by PD facilitators valuing multiple ideas from TAs about how they make sense of science practice–based instruction, or by asking TAs to engage in situations that will promote cognitive conflict and sense-making about the challenges of instruction in these contexts.

Limitations and Future Directions

A central component of our analytical approach was our use of stimulated recall, which allowed us to uncover TA instructor reasoning. One limitation of this approach was that the in-class episodes TAs reflected on were chosen by an education researcher. This could introduce some selection bias and does not account for all the practices an individual TA might have implemented. Another limitation of our analytical approach was our choice to analyze a single timepoint of TA instructor implementation. Future work should consider analyzing multiple points of TA instruction to holistically understand each TAs implementation. Investigating multiple time points over a longer period (i.e., semesters or years) would also allow for implementation and mechanisms of learning to be further explored.

Another limitation of the study was the limited data collection. Though our sample of TAs allowed us to see common ideas across multiple individuals, it was limited in diversity (e.g., more undergraduate than graduate students TAs). Future work could explore TA instructor implementation across a larger, more diverse sample. This could allow for better understanding of implementation practices but could also allow investigation of how TAs' prior knowledge and experiences might influence their forms of instruction. Finally, it is important to acknowledge that this study and its findings were done within a single context (the AIM-Bio curriculum). The TAs investigated all taught the same course and participated in the same PD. This component of our study facilitated our deep exploration of instructor implementation. However, it also limits our ability to disentangle the role that curriculum or PD may have played in our findings about TAs. To learn about the potential generalizability of our findings, future work should consider investigating TA science practice-based instruction across curricula to look for commonalities or to understand affordances of PD.

ACKNOWLEDGMENTS

We would like to gratefully acknowledge the contributions of Emily Dykstra in helping us to facilitate collection of TA data and the undergraduate and graduate students who generously contributed their time and energy as participants in our study. We are also grateful to Dr. Tessa Andrews and to the University of Georgia's Biology Education Research Group (BERG) for their feedback on the manuscript. Support for this work was provided by funding from the National Science Foundation-Improving Undergraduate Science Education (DUE-2020788).

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