Impactful experiences and their effect on learning assistant epistemological development

Ben Lutz[1] and Laura Ríos[2]

[1]*Department of Mechanical Engineering, California Polytechnic State University, 1 Grand Avenue, San Luis Obispo, California 93407, USA*

[2]*Department of Physics, California Polytechnic State University, 1 Grand Avenue, San Luis Obispo, California 93407, USA*

(Received 9 November 2021; accepted 14 September 2022; published 14 November 2022)

Learning assistants (LAs) are peer educators who work alongside faculty to facilitate active learning activities and help students develop conceptual understanding. LAs and LA training programs are becoming increasingly prevalent in science, technology, engineering, and mathematics (STEM) gateway courses in the United States, and research continues to document the positive impacts on students and LAs in LA-facilitated classrooms. While evidence accumulates regarding positive student impact, relatively less work has investigated the ways LAs themselves might also be impacted by their participation in these programs. To improve LA training and student learning in STEM, it is vital that educators better understand the ways the experiences of LAs can promote personal and professional growth as members of the STEM community. To address this gap, we explored the epistemological development of LAs who participated in an LA program (i.e., pedagogy training and classroom practice) at a large, public, teaching-focused university. LAs participated in semi-structured interviews at the beginning and end of the academic term and completed bi-weekly reflections where they described impactful events and challenges. Using qualitative coding, we operationalized Baxter Magolda's epistemological reflection model to identify the impactful experiences that provoke epistemological development or reorientation. Our findings highlight three impactful experiences that help promote epistemological development for LAs: (i) recognizing the importance of language and listening; (ii) observing more knowledgeable others struggle with content; and (iii) providing students with the "wrong" answer to a question. We argue that these experiences can promote epistemological development in ways that help LAs become more effective in facilitating student learning and, ultimately, more thoughtful members of STEM disciplines. By working to create spaces for LAs to have these impactful experiences in training and preparation, educators can promote epistemological growth in ways that benefit both LAs and the students they serve.

DOI: 10.1103/PhysRevPhysEducRes.18.020133

I. INTRODUCTION AND BACKGROUND

Learning assistants (LAs) are near peers—undergraduates who receive training in content and pedagogy and supplement classroom learning activities by helping faculty facilitate group discussion. LA programs are becoming increasingly popular across a range of STEM disciplines as research continues to demonstrate substantial positive impacts on a wide range of student outcomes [1]. And although existing research has illustrated the positive impacts of the LAs on the learning and development of students in LA-facilitated classrooms [2–6], relatively little work has explored the role of personal and professional development of the LAs themselves. To improve LA training and preparation, and therefore student learning and development, it is important that educators better understand how the LA training programs might promote epistemological development in ways that can further enhance student success.

The LA model is well known to the physics education research community and described in detail in Ref. [7]. Here, we broadly describe three arms of the LA model: (i) content preparation to learn domain knowledge; (ii) pedagogical training in a seminar for first-time LAs; and (iii) classroom practice. Content preparation is conducted by the instructor of record, and LAs engage with the same activities and content as the student, work with faculty to anticipate student difficulties or ideas, and strategize different approaches for facilitating student discussion and learning around particular concepts. The goal of the content preparation is to prepare LAs in the domain knowledge relevant to a given class or lesson. In the pedagogical training seminar, LAs focus on relevant learning science such as metacognition and the role of

formative assessments. Many curricula also touch on important topics in diversity and equity, such as stereotype threat and sexist normative discourse. These two forms of training (i.e., pedagogy and content) are combined for LAs when they enter the classroom and work with students in active learning environments.

Research has also noted positive impacts on LAs as a result of their participation in these programs. Participation in LA programs can result in the development of valuable pedagogical skills and help LAs develop an identity and membership associated with STEM education. For example, Ref. [8] used concepts of *communities of practice* to explore LA experiences in physics. Their findings point to the ways that engagement with educational communities of physics faculty can increase LA learning, interest, and identity development. More recently, Ref. [9] argued that by positioning LAs as student partners in education, they can become members in a community of practice and use their experiences as learners to inform educational and pedagogical choices for instructors. Another study [10] demonstrated how a classroom simulation tool could improve LA skills related to different pedagogical strategies such as leading questions, wait time, or divergent questioning to name a few. While these studies demonstrate positive gains for LAs, areas of epistemological development remain underexplored in the literature. Epistemology is a critical dimension of LA personal and professional development because understanding how LAs view knowledge and ways of knowing can have profound impacts on their approaches and interactions with students. A study in how LA epistemology impacts approaches and interactions with students helps to contextualize existing research on how the LA model informs teacher practice [11] and how teacher epistemology generally informs instructional choices [12].

Also relevant to the LA model are concepts of situated learning [13] and legitimate peripheral participation [14]. Lave and Wenger note that learning is a *situated* activity in that it is shaped by the context in which the learning takes place. In the case of LAs, that context includes other faculty, LAs, and students; thus, they interact with knowledge and concepts in ways that are different from their experiences as students in class. Therefore, while LAs might already be familiar with the topics taught in the classes they work in, their new roles require different ways of engaging with and coming to understand those topics. By interacting with and learning the content *as learning assistants*, they come to understand concepts in ways that are different from students and faculty. This shift in context can promote epistemological development or refinements, revisions, updates, etc., to their own mental model of teaching and learning in STEM.

Further, the concept of *legitimate peripheral participation* is important in understanding the ways in which LAs come into their roles and how they learn to interact with students. Lave and Wenger note that when novices learn to engage in a given practice, they begin on the periphery of that practice, performing what are relatively straightforward tasks but that are nonetheless important to the broader goals of that practice. Over time and under the supervision of a mentor, they integrate these aspects to more fully engage in the central practice of a given community. For example, LAs begin the program by learning how to perform "talk moves" that are designed to encourage students in class to engage with concepts and articulate their own understanding to others. At first, these moves might be understood as relatively prescriptive and function as a sort of "script" to follow when interacting with students. However, as LAs progress through the program, they learn about relevant learning theories and practices that support these different moves and come to understand how to develop their own talk moves or habits informed by these theories. Eventually, LAs take on more central roles in supporting student learning and therefore move closer to the core of the practice. Importantly, this progression takes place under the guidance of both LA pedagogy seminar faculty and the instructors they work for (and in some cases, more experienced LAs). They enter the community of practice as novices who function on the peripheries and, through interaction with and mentoring from various content and pedagogy experts, become more central to the broader enterprise of supporting student learning and development.

Theories of situated learning and communities of practice are relevant to epistemology because of the focus on the relationship between learning contexts on the one hand and ways of knowing on the other. That is, how and where something is learned will influence the learner's beliefs about knowledge and indeed what is knowable in that context. Research has shown how understanding of core engineering concepts changes based on the context in which those concepts might be used and the ways they are represented [15,16]. More recently, researchers have demonstrated how acquiring and developing scientific practices through engagement in authentic activities can affect epistemic reasoning and development [17]. By helping LAs integrate into a broader community of scientists and engineers, they are interacting with similar knowledge, but in fundamentally different ways than before. This shift in learning context thus results in changes to how LAs might relate to that same knowledge.

We focus on epistemological development because we argue that LA programs can be most effective when LA training is aligned with and tailored to the developmental needs of the LAs. By understanding LA epistemological development and impactful experiences that encourage growth, training programs can create opportunities designed to help LAs progress in their epistemological development. We argue that this process can make LAs more effective in classroom settings and better prepare them as future educators and scientists.

The purpose of this article is twofold. First, we will identify and examine impactful experiences that facilitated epistemological development for LAs in our study. To do so, we examine the experiences of LAs who expressed an epistemological growth or reorientation moment during an academic term (in this case, a 10-week quarter). Second, in connecting research to practice, we synthesize our findings alongside existing literature recommend ways that educators might help facilitate these kinds of shifts in both LA pedagogy seminars as well as in-class activities. We combine educational theories alongside practical experiences that can help educators develop more effective LA training and preparation experiences in ways that promote epistemological growth. We argue that by helping LAs develop more sophisticated ways of knowing and reasoning, they will be more effective in their roles as LAs and help the students they serve develop these ways of knowing through modeling. To that end, we pose the following research question:

1. What kinds of events or experiences facilitate epistemological development for LAs in STEM programs?

II. THEORETICAL FRAMEWORK

To address this research question, we turn to Baxter Magolda's epistemological reflection model [18]. Baxter Magolda's work is in the tradition of Piagetian developmental models, which describe students' cognitive development over time. In particular, Baxter Magolda builds on theories from Perry's model of intellectual development [19] in ways that offer both higher granularity and consider gendered patterns and differences. Baxter Magolda focuses on student development by exploring perspectives about common aspects of college learning environments. Baxter Magolda showed that as students interact with increasingly complex ideas and different perspectives, their beliefs about knowledge, authority, and learning change from relatively simple, universally applicable models about the world to ones that are more complex and responsive to unique contexts. The epistemological reflection model characterizes the different points of development in the ways that college students come to know and reason about salient aspects of their educational contexts. The model describes student development in two primary dimensions: *domains* and *ways of knowing*. Domains represent the different actors within educational settings (i.e., the role of learners, peers, instructors, and LAs) as well as beliefs about certainty with which something can be known (i.e., nature of knowledge) and how learning should be assessed (i.e., evaluation).

Ways of knowing represent the different qualitative categories that describe, holistically, how college students perceive these different domains. The progression in ways of knowing offers a developmental model that describes how student beliefs and reasoning patterns change over time regarding different domains of the framework. For the present research, we will focus on the first two categories of the model: absolute and transitional. *Absolute* knowing is characterized by beliefs related to the "banking model" of education where knowledge is highly constrained and controlled by authorities. Students in this stage view knowledge can be asserted with a high degree of certainty (i.e., it is either right or wrong) and believe that it is professors who possess this knowledge and dispense it to students unidirectionally. To know is, therefore, to be able to demonstrate possession of knowledge and, typically, facts about a subject. *Transitional* knowing retains some aspects of the banking model of education but is also characterized by a new focus on the role of others (i.e., peers) in supporting learning and the importance of practical knowledge and application. That is, knowledge is still "stuff" that a professor has and which students can acquire and share with each other, but knowing takes on a practical emphasis and more importance is placed on understanding concepts rather than simply remembering facts. These two categories comprise the vast majority of students in their first three years of undergraduate studies, which is the population involved in the present research.

Shown in Table I is a modified version of Baxter Magolda's [20] (p. 30) epistemological reflection model that accounts for the unique role of the LA. Given the unique role of LAs in educational settings, we expanded the model to include an additional domain. Specifically, we have added the *role of learning assistant* to better account for the distinct beliefs that might exist around how LAs perceive themselves relative to peers, students, and the instructors they work with [21].

Notably, the full model contains two additional ways of knowing (i.e., independent and contextual), but these were not observed in the present work and so they are not included in our discussion. Table I offers an overview of the different permutations of ways of knowing and domains. For an operationalized codebook, see Tables IV and V in Appendix A.

We employ Baxter Magolda's framework because it highlights the different roles and domains that are relevant to teaching and learning in college. The framework also offers a way to focus on how the practices LAs implement practices that are rooted in their beliefs about knowledge, teaching, and learning in STEM classrooms. Specifically, we used this model to observe changes in students' epistemologies based on the ways they talked about these different dimensions of the learning environment.

There are a few important observations to make about this model. First, from a conceptual standpoint, domains and ways of knowing operate orthogonally to each other. That is, when students describe their beliefs, they do so at the intersection of ways of knowing and domains. We will describe the process in more detail below, but the implication is that passages are analyzed in terms of *both* the domain being referred to *and* the way of knowing espoused in that passage. It is the combination of these

TABLE I. Overview of absolute and transitional ways of knowing within the epistemological reflection model.

Domain	Absolute knowing	Transitional knowing
Role of learner	-Obtains knowledge from instructor	-Understands knowledge
Role of instructor	-Communicates knowledge appropriately	-Uses methods aimed at understanding -Employs methods to apply knowledge
Role of peers	-Share materials -Explain what they have learned to each other	-Provide active exchanges
Evaluation	-Provides vehicle to show instructor what was learned	-Measures students' understanding of the material
Nature of knowledge	-Is certain or absolute	-Is partially certain and partially uncertain
Role of learning assistant*	-Offers useful explanations that are different from the professor -Asks students questions to make them think	-Listens to student responses to questions to improve explanation -Attends to affective dimensions of learning

*This domain was added to the Baxter Magolda Framework during this research.

codes that allows us to observe patterns within these different permutations.

Second, although the model is developmental, growth from one way of knowing to the next—or across different domains—is nonmonotonic. That is, a student might express beliefs consistent with transitional ways of knowing about, for example, evaluation at one point in time and absolute at another later point; this does not mean that the student has somehow regressed. However, as students develop epistemologically, the preponderance of one way of knowing over others does tend to emerge as the dominant pattern for a time. For this work, this means that participants in this study were not labeled as one kind of knower or another. Rather, individual units of analysis (discussed below) were examined at the aggregate level to explore patterns across participants and over time.

III. METHODS

This research used qualitative analysis that combined both *a priori* and emergent coding to investigate epistemological development and reorientation of LAs. We combined pre and post semistructured interviews with bi-weekly (i.e., every other week) reflections to identify and explore impactful events that seemed to facilitate epistemological development along one or more of the domains noted in Table I. We used *a priori* codes informed by the epistemological reflection model described above as well as prior research from the authors which operationalizes and integrates the *role of the LA* into the existing framework [21]. In this work, Ríos and Lutz use the epistemological reflection model to demonstrate the ways in which LAs operate in roles that are not quite instructor, peer, student, nor some kind of linear combination of these typical roles (for a full discussion of the concept of orthogonality, see Ref. [21]). Analysis used the framework to identify language indicative of particular ways of knowing within the expanded epistemological reflection model. Self-reported demographic information of the research participants is included in Table II.

A. Sample and data collection

The research participants were LAs enrolled in the learning assistant pedagogy seminar during an academic year. In this seminar, first- and second-time LAs learn about questioning strategies, metacognition, mental models, and other pedagogical content in order to prepare them for facilitating discussion in a classroom. Participants facilitated courses in introductory physics, astronomy, geology, and engineering. Evident in Table III is that most LAs in this study supported introductory physics studio classrooms.

We collected two data sources: the first were bi-weekly written reflections deployed to students in the LA seminar as part of their regular coursework. The reflections asked LAs to describe a significant challenge they encountered in their role as LAs and to elaborate on how that challenge was supported by others, what they learned, and how it influenced their overall approach with students. The reflective journals were adapted from Ref. [22] to capture significant experiences over time.

The second form of data collection was pre and post semistructured interviews with LAs at the beginning and

TABLE II. Demographic information of LA participants.

Pronouns	Number of participants
He/him/his	10
She/her/hers	9
Not identified	1
Race or ethnicity	
White	11
Asian	5
Hispanic or Latino	1
More than one	3

TABLE III. Overview of courses the LA participants supported.

Courses supported	Number of participants
PHYS 141 (calculus-based introductory physics)	7
PHYS 121 (algebra-based introductory physics)	2
PHYS 132 (waves and vibrations)	3
PHYS 133 (introductory electricity & magnetism)	2
Geology 201 (physical geology)	2
Astro 102 (introduction to stars and galaxies)	2
ME 212 (engineering dynamics)	2

end of the quarter. The pre-interview protocol asked the LAs questions about how they would assess, evaluate, or describe their knowledge of STEM topics to someone else; how they might prove knowledge to someone else; and the importance of the topics of the courses they serve. For example, questions in the first initial interview asked students to describe things they would do or say when communicating a complex concept to someone else. They also asked questions about how participants might prove they understood a concept and what kind of evidence they might offer. These interviews served as a baseline for participants' epistemological beliefs.

The follow-up interviews, conducted at the end of the 10-week quarter, focused on LA classroom experiences and asked them to reflect on different successes and challenges. Here, we asked participants how their experiences might have impacted their beliefs about teaching and learning and interactions with students. In addition, these follow-up interviews provided a space for participants to elaborate on specific experiences they documented in their reflections. As a result, follow-up interviews were also used to provide a source of triangulation for the data collected via reflections. Taken together, the two interviews combined with the bi-weekly reflections offer a holistic view of LA experiences and development throughout the academic term. Both protocols and reflective journal prompts are included in Appendix B.

Data collection was approved by the IRB at the present university (IRB #2019-220). All interview data were transcribed by a professional transcription service and scrubbed of identifying information prior to analysis. Participants were also given pseudonyms to protect privacy and confidentiality.

B. Data analysis

We used *a priori* codes developed by Baxter Magolda [20] and expanded on by Ref. [21]. Each unit of analysis was coded in terms of both the domain referred to (Table IV) and way of knowing indicated by the particular passage (Table V). These codes offered a means to characterize participant beliefs and patterns in epistemology. Analysis was primarily focused on interview data and used the reflection data to triangulate findings when possible. The ways of knowing were identified based on participant language that aligned with the different domains of Baxter Magolda's model as well as through examples provided in the original publication [20].

To illuminate the coding process, we provide an example quote and explanation of the coding process and rationale. The following quote from Peyton was coded as transitional

> Interviewer: Why might it be important for someone to understand physics?
> Peyton: *[I]f you [the student in class] understand something and can do for your—do it for yourself then people might be, wow, that's cool you were able to do that. But they have no way to relate with you. Or be able to have more of a discussion or figure out something they thought was cool themselves. But if you have the ability to explain it, you can create interest in other people and add more learning. And have them make discoveries of their own and add to your idea. And if you only think with your own brain, then you can't develop anything further. You have to be able to talk with other people to continue with what your understanding and figuring out more.*

Here, Peyton describes that, as a student, explaining or "doing" something for "yourself" is not sufficient to establish understanding. Instead, Peyton expresses that a good demonstration of learning is how "you can create interest in other people *and add more learning*" (emphasis added). To Peyton, learning is bolstered in conversation and discussion with others, and thus the role of the learner is to engage in those conversations. Examination of Table I shows that the "Role of learner" for a transitional epistemological orientation is "understands knowledge" (as opposed to "acquires knowledge")." Here, Peyton describes the behavior of the learner needed to demonstrate understanding; namely, discussion with others. Debate among peers is a key element to a transitional epistemology; part of the *role of the learner* is to seek out different perspectives. However, we note again that we do not classify Peyton holistically as a "transitional knower." Rather, this utterance indicates a moment in time that is best categorized within the framework as a transitional epistemological belief.

In sum, because Peyton says that knowledge has to be understood ("be able to talk with other people to continue with your understanding"), this utterance was coded as transitional. This analytic approach was followed for each unit of analysis.

An important note about these data is that epistemological development did not occur all at once or even necessarily remain consistent for LAs over time or across domains. This finding is also consistent with other work that describes epistemological development as nonmonotonic [23]. It is therefore possible that some LAs expressed

beliefs consistent with *transitional* ways of knowing in their pre-interviews and *absolute* ways of knowing in their post-interviews. This growth occurs gradually for students and can evolve differently across different domains. Therefore, while it appears that the LA experience (i.e., in-class interactions, work with professors, and pedagogy seminar) resulted in epistemological growth in the aggregate, these shifts are not necessarily internally consistent for a given individual within the current data set.

Nonetheless, for some, these shifts were more pronounced and seemed to result in substantial changes throughout the academic term. Baxter Magolda notes that people use particular sets of assumptions and models (i.e., ways of knowing) in ways that are useful until they encounter dissonance with those models. When the dissonance is great enough, "individuals revise their assumptions to accommodate the new experience, resulting in growth toward more complex meaning making" (Ref. [24] p. 622). We therefore examined transcripts and reflective journal data for events or experiences that prompted dissonance and encourage revisions to their epistemological beliefs.

In the present study, the epistemological patterns we observed were almost exclusively from *absolute* or *transitional* ways of knowing. This finding is consistent with the research of Baxter Magolda and others, who also found that students at similar points in their academic careers (i.e., second and third year in college) articulated similar epistemological beliefs.

C. Credibility and trustworthiness

To establish the credibility and trustworthiness of the present findings, we followed recommendations by Ref. [25] regarding unitization and negotiated agreement. For interview data, we classified units of analysis as participant responses to a single line of questioning from the interviewer. When the interviewer asked for elaboration or an example, both the initial response and the example were included in the unit of analysis. For reflective journal data, the unit of analysis was the set of responses within a given week. By establishing agreement on units of analysis, the authors were able to make more accurate and useful comparisons when achieving consensus on codes applied.

Once units of analysis were established and agreed upon, the authors engaged in negotiated agreement processes. Specifically, we conducted collaborative coding with 9 of the 36 interview transcripts, selected at random. Collaborative coding took place in two main phases. First, the authors read transcripts together and discussed the codes they applied and their rationale for selecting a given domain and way of knowing. This process led to the development of operational definitions that were then used for the second phase of collaborative coding (Tables IV and V). In the second phase, the authors coded transcripts independently and met to normalize and reach agreement. During this phase, the authors compared codes applied to the same segments and argued to consensus where there were discrepancies. This process helped to revise and refine operational definitions within the codebook and these codes were then used to analyze the remainder of the interviews and reflective journal entries. By working iteratively and collaboratively with the codebook, the authors reached agreement in terms of how to consistently apply codes for subsequent analysis.

Moreover, both authors kept detailed audit trails of their analytic process and the evolution of their thinking throughout the project. We composed analytic memos in line with recommendations with Ref. [26] in which we documented our thoughts about the data and kept a running record of how our understanding evolved over time. These memos were reviewed during analysis meetings and formed the basis for documenting decisions made regarding how to proceed with analysis. By keeping a detailed record of the ways that our codebook evolved over time, we made key analytic decisions transparent and thereby enhanced the trustworthiness of our findings [27].

IV. RESULTS

The purpose of this research is (i) to identify experiences for LAs that appear to promote epistemological growth and (ii) to do so in ways that might inform efforts for LA training and preparation. As LAs engaged with the program, they noted different experiences that challenged them in different ways and which created the conditions for the dissonance that sparks epistemological growth. We identified three such experiences and will outline them in further detail in the following sections. First, when LAs experienced disconnects between their *language* and that of their students, they were prompted to confront the diverse ways that individuals might come to understand a concept and noted the importance of listening for effective communication. Second, experiences where LAs observed instructors and more experienced LAs *struggle with challenging ideas* helped them understand that even experts (i.e., authorities) can sometimes be wrong or unsure about ideas. Finally, building on the second experience, when LAs provided students with the *wrong answer to a question*, these experiences prompted LAs to reconsider their roles in the classroom as it pertained to co-constructing knowledge. We elaborate on each of these events in the following section with specific quotes and examples that demonstrate epistemological growth.

In the following sections, we will provide examples through quotes from LAs in this study in which they both describe and reflect on impactful experiences. We will focus on the ways of knowing because they are the broad, qualitative categories that characterize different belief systems and worldviews.

We focus on ways of knowing for reasons both theoretical and methodological. First, epistemological growth

occurs gradually and nonuniformly across the various domains. According to the theoretical model, as students take on new ways of knowing and reasoning, beliefs about different dimensions of their educational context change accordingly. As a result, epistemological growth from one way of knowing to another (e.g., from absolute to transitional) both shapes and is shaped by beliefs about different domains. In this way, growth does not occur along a domain *per se*, but is characterized by the changes in one's beliefs about, for instance, the role of instructors or peers or LAs. The domains may be better understood as useful and relevant dimensions to attend to and probe for in assessing changes in broader epistemological growth. Moreover, in the process of coding, LAs might refer to multiple domains and roles in a given passage or unit of analysis. Therefore, although our codebook allows us to separately identify domains and ways of knowing in the data (e.g., distinguish role of learner and role of LA), the *analysis* of these codes must take into account that growth is observed across different domains at different times and is expressed in different ways. It is therefore the process of examining *across* the different domains that one's primary way of knowing can be evaluated. As such, we report primarily on ways of knowing as an overall pattern of beliefs, ideas, notions, and conceptions encompassing the roles described by the domains.

A. Impactful experience #1: Recognizing the importance of language

LAs in this research were affected by disconnects or gaps in language related to learning and communication with their students. Many LAs initially noted that their role in facilitating learning was related to explaining an idea clearly to a student in a way that resembled dispensing knowledge (*absolute knowing*). For example, in an initial interview with Adrian, he describes his own process for communicating about a complicated concept with students.

> *When I try and explain a concept to someone, I mean, I guess, in general, I would try and explain it the way that makes most sense to me, but a lot of times when I'm trying to explain stuff to people I kind of like figure it out as I go. I kind of learn how to explain it as I explain it is what I find. I don't have precanned solutions to most problems. It's kind of like on the fly. And so I wouldn't know a general idea of how would I explain something other than I would just explain it how it makes sense to me and hope that that was—a lot of times I think if you can give them something to look at, some kind of maybe an equation or drawing that models the situation, they can get some kind of weird intuitive sense for how it works but still not be able to replicate or explain it.* [Adrian, Initial Interview, Physics for STEM Majors]

In this quote, Adrian describes in a general way what constitutes a good explanation and how he would communicate that he knows a topic to someone else. He describes that his approach is responsive ("on the fly"), but based on his own evaluation of the topic or knowledge ("I would just explain it how it makes sense to me"). Thus, for Adrian, successful communication is primarily based whether the explanation makes sense to him. He does not articulate here in what ways, if any, the other person's, e.g., mental model affects his own interpretation of either the topic, or how to explain it. Adrian does describe checking in with the student to see what resonates or what experiences they might have that he can leverage for explanatory power ("if you can give them something to look at"), but if knowledge is *absolute*, then it might not matter how it is or is not connected to students' prior understanding.

Similar sentiments were expressed by Taylor, who described learning and his role in it as one of possessing and receiving. In the following quote, Taylor discusses the descriptions of providing information (i.e., knowledge) and the responsibility of the recipient of knowledge are consistent with *absolute* ways of knowing.

> *Well, maybe I'm naïve, but just, I feel like that's all a person can do to help someone learn, is provide the information, show how that information can be used, show how that information is valid, is true, and you can also help somebody understand how to use that information, guide them through using the information. But there's still a huge responsibility on the recipient of that information to kind of learn it and understand it. So if a concept is taught to a student, they're given this information, they are given examples. They have the LA to kind of bounce back and forth from ask questions.* [Taylor, Follow-up Interview, Physics for STEM Majors]

Of note, Taylor begins his description with the qualifier, "maybe I'm naïve, but…" We believe this is notable because the LA seminar has explicit discussions on epistemological resources [28] and how deeply enduring experiential learning can be. Regardless, Taylor's view rests on the verb "show"—the LA "shows how that information is used," indicating that he dispenses information in addition to perhaps procedural or system knowledge on how to use or assess knowledge. While there is an acceptance that the learner must be engaged, the learner is still a *recipient* and not a *generator* of knowledge ("But there's still a huge responsibility on the recipient of that information").

Throughout the term, however, LAs had experiences with students that disrupted these notions of "communication as explaining clearly," seemingly generating dissonance with their epistemological beliefs. In the following reflective journal response, Terry describes an experience in which differences in language use between her and a student resulted in less-than-optimal learning.

> *My biggest challenge in weeks 5–6 was figuring out how to explain the concepts in a way that is simple and easily understood, but also thorough enough to answer a*

question. I think that this was challenging because I sometimes ramble and talk to the students about aspects of a problem that might not be helpful. I encountered this problem when I was a tutor, but it was easier for me then to help one student at a time. [If I could do things differently], I would try and ask the students more questions to explain their thoughts before giving input, because that helps me understand their footing, so I can help on their terms and using the language that they are using so we both understand each other. […] Next time, I will try and ask more questions of the students to try and help them find the answers on their own, and so I understand their perspectives better. This has helped me to make my approach more friendly and conversational which I think helps the student feel more comfortable. [Terry, Reflective Journal, Physics for STEM Majors]

Here, Terry reflects on an interaction between her and a student where a lack of questioning on her part led her to explain something in ways that were unhelpful. The focus here is still on explaining in ways that are "simple and easily understood," and thus suggests a more *absolute* way of knowing. At the same time, however, Terry recognizes that by asking questions and listening to student responses, she can be more effective in facilitating learning ("helps me better understand their footing"). Listening and using students' own language indicates a *transitional* epistemology, and this passage suggests that this experience with language and communication created space to reorganize her model of the role of communication in learning. Terry recognizes that learning was not only about providing information, but also listening to students to communicate most effectively (*I can help on their terms and using the language that they are using so we both understand each other*). By using students' own language, Terry notes how she can create a shared understanding in ways that will improve learning. These kinds of experiences helped LAs recognize the role of listening in effective communication and learning and prompted them to reassess their own beliefs about teaching, learning, and knowledge creation.

Communication and language were also noted in follow-up interviews. LAs described the importance of language in being able to set aside their own needs to actively listen for students' mental models without judgment. In the following passage, Wyatt answers to a follow-up question about effectiveness in the classroom. Wyatt notes how listening is vital to understanding students' confusion and responding effectively.

I think it's important to listen because if you hear one part and you think that that's where they're struggling, and then you start directing towards that—if you start going towards that direction, maybe that's not the entirety of the question. So I think clarifying what the student's question actually is was how I showed that I was listening. [Wyatt, Follow-up Interview, Dynamics]

The emphasis is on not only listening for shared language to make communication smoother, but on listening deeply to make sure she understands "what the student's question actually is." Further, Wyatt now accepted that thought is becoming restructured through speech, and generating a dialogue between the LA and the student in which knowledge is negotiated ("if you start going towards that direction, maybe that's not the entirety of the question.") This reflects a belief about her role that is not only about providing accurate information (i.e., *absolute*), but doing so in ways that recognize the importance of other perspectives and ways of articulating ideas (i.e., *transitional*).

Relatedly, questioning also becomes a critical part of listening that helps her better assess prior knowledge and understanding. By asking questions and actively listening, LAs can incorporate that prior knowledge into their interactions with students in ways that improve learning.

Interviewer: How has your thinking about teaching and learning has changed from your work as an LA?

I think, when you're [the student] trying to explain something while you're still learning it, sometimes you don't have all the pieces put together, and all the words that you use—it's kind of hard to put it all together, and to synthesize in a verbal way. And yeah. So that's how I understand it, in that communication between LA and student. Being able to realize the way they're using language and recognize that sometimes someone has a concept in their head, but they can't put it into words. Or they're putting it into words that don't quite click with me. And so having to—how I wrote. Ask more questions, maybe give some examples, and try and—instead of just listening to what they're saying at face value, try and work around that, and understand what they're thinking. Because that's something I understand, too, because sometimes I feel like I understand something. But then, if I have to explain it, it can be very, very hard to export that out and into language. And so that's another—that's something that has been pretty important, for me to understand students better. [Terry, Follow-up Interview, Physics for STEM Majors]

For Terry, being a good listener and using students' language helps the students get from their current understanding to where they want to be. She alludes to the difficulty during the learning process to verbalize your thoughts ("it's kind of hard to put it all together, and to synthesize it in a verbal way") and how an LA can aid a student by using or encouraging speech as a thinking device ("sometimes someone has a concept in their head, but they can't put it into words"). When students are still learning a concept, they have not fully developed the language to talk about it in the ways that more knowledgeable others might (*all the words that you use—it's kind of hard to put it all together*). This sounds very typical of LA training; where we obtain insight into her epistemological stance is the way she

internalizes her role, evident by the utterance, "Or they're putting it into words that don't quite click with me." Here, her role is co-constructor of knowledge, accepting that the student may "know" but the lack of shared language is keeping them from coming to a shared *understanding*. By working to hear students and tease out the "concept in their head," Terry uses students' language and thus prior knowledge to help co-create a better understanding of a given topic. As LAs grappled with the complexities inherent in working with other perspectives, ideas, and language, LA experiences related to miscommunications or breakdowns offered opportunities to rethink their own beliefs about teaching, learning, and understanding in ways that promoted epistemological growth.

B. Impactful experience #2: Seeing others struggle with content

For LAs in this research, observing other, more experienced individuals struggle with material helped them recognize that even experts can be "wrong" or might not have immediate answers to student questions. As LAs worked with faculty and other experienced LAs throughout the program, they noticed times when those individuals struggled with difficult concepts or were unable to immediately address a student question. Most LAs enter the program with views of knowledge and learning that are consistent with the "banking model" of education [29], and thus see teaching and learning as a means of transmission of knowledge from one individual to another. For some students, content proficiency was a critical component of their effectiveness with students and this focus on content preparation is reflected in their beliefs about effective teaching and learning. For example, in the following excerpt, an LA describes the importance of "knowing the subject" for effective teaching.

> *Yeah. I think it's really important, definitely to know your subject and to really know the details. And then from there, I think you can be a really effective teacher. Because there are some things that I know pretty well […], but there are also a lot of concepts that I was really shaky on […]. And so I think especially in these classes that cover a lot of material like the physics classes, which cover a ton of things. It's super important to really know the concepts that are being taught, yeah.* [Riley, Follow-up Interview, Introductory Electricity and Magnetism]

Riley emphasizes that the starting point for effective instruction is strong content knowledge ("And then from there, I think you can be a really effective teacher"), and mentions how important it is to "really know the concepts that are being taught." Certainly, domain knowledge is an important aspect of supporting a course, evidenced by the content preparation arm of the LA model. However, for many LAs, content knowledge was his *sole* criterion for effectiveness (despite significant messaging that it is not expected of the LAs to be content experts). Riley notes how important it is to "really know the details" of the subject. Here, being a content expert and having a strong grasp of the topic is what makes someone an effective educator.

But LAs also noticed how their instructors would struggle with the content or student questions. Seeing more knowledgeable others struggle with challenging material helped LAs recognize that it was acceptable to not know everything and validated their own struggles as they prepared to help students. In the following quote, Riley shares an experience where he observed an expert (i.e., the instructor of the class he supported) struggle with students' questions during class.

> *[Seeing my professor struggle with questions] definitely changed my perception on teaching as a whole. Because it's super, super, super hard to be prepared for every possible question that a student can have or every possible angle that a problem has or—so if someone asked me something I totally wasn't prepared for that question or that way of thinking, then it's definitely an awkward situation. But it's made sympathize to teachers a lot because I sort of I've been in that situation that before. And so I kind of understand there's a lot more going on, so yeah [laughter].* [Riley, Follow-up Interview, Introductory Electricity and Magnetism]

The experience helped Riley recognize that there are things that experts might be unprepared for as they engage with learners ("it's super, super, super hard to be prepared for every possible question that a student can have or every possible angle that a problem has or…"). Riley starts to recognize that it might be impossible to prepare for everything because individuals and their unique perspectives will always introduce new questions. Experts often organize concepts and ideas differently than novices (Refs. [23,30]), and so instructors might not always be able to anticipate the kinds of questions students might ask and might thus appear less knowledgeable or unprepared. Witnessing this struggle or lack of immediate knowledge was impactful for Riley, as it helped him see how knowledge is not necessarily something that is contained in experts and transmitted to students, but rather something that is subject to local questions and unique challenges in context, which is consistent with a *transitional* way of knowing. That is, rather than seeing knowledge as something that experts possess and can therefore readily summon, it is something that is more tentative and that exists in the interactions between learners and educators.

This recognition that struggle is both normal and productive created some dissonance for LAs about authority and knowledge (i.e., who can or should struggle in a classroom) and created space to reorganize their own models and beliefs about learning and understanding.

Witnessing this struggle also helped LAs achieve more productive interactions with students. By passing along the lessons they were learning about the nature of struggle, LAs helped students see that, in many cases, struggle is vital to the learning process. The following quote illustrates how this struggle is productive and can be effective for student learning.

> *It's hard to walk that line because you're in a sort of authority position. But you also like being able to make yourself human and vulnerable can be really powerful in ways that you're demonstrating that struggle and validating, right, that you can validate their experiences and vice versa even.* [Kendall, Follow-up Interview, Physics for STEM Majors]

Here, Kendall is elaborating on ways the LAs can best put students at ease in the classroom. In addition to needing to know the content, for Kendall, it is important to show vulnerability in ways that validate students' own struggles with learning the material.

LAs began to interact with students in ways that both "validate their experiences" and mitigate barriers to effective learning (e.g., students not wanting to appear unintelligent or ask a "dumb question"). Witnessing struggle provided the space for LAs to revise their beliefs and ideas around the learning process and the important parts of it. Struggle both provided opportunities for individuals to be vulnerable with each other and helped LAs more readily see the ways in which learning is collaborative and indeed driven by questions for which there is currently no satisfactory explanation.

C. Impactful experience #3: Offering the "wrong" answer to students in class

Another experience that influenced epistemological growth involved getting an answer wrong during interactions with students. For LAs in this study, getting an answer wrong provided an opportunity to reflect on their role in the classroom and the best ways to facilitate student learning. This experience is distinct from simply recognizing that it is acceptable to be underprepared or to struggle (i.e., impactful experience #2) because it seemed to produce a stronger dissonance and reorganization of beliefs about knowledge and learning. To illustrate this point, we highlight the experience of Sidney,[1] an LA who struggled after providing students with the wrong answer to a given problem during class. In a journal response, he offered the following reflection about the challenge of getting an answer wrong.

> *[My biggest challenge this week was] being wrong about my answers. [It was challenging because] I didn't want to mislead my students and have them do worse in the course because of me. [To address this challenge], I directed the question back to them and asked how they would approach the problem.* [Sidney, Reflective Journal Week 4, Waves and Vibrations]

Here, Sidney is concerned that he might be misleading students, which could harm subsequent learning. While LAs are encouraged to ask students questions to elicit understanding, Sidney seems to use the approach to deflect and distract from a lack of knowledge. The focus on appearing knowledgeable and being correct is consistent with *absolute* ways of knowing. Rather than recognize the collaborative, co-constructed nature of knowledge, it is important to possess the correct information when it is questioned again. Nonetheless, making sure he was prepared and correct in his answers was important for Sidney, and he chose to further reflect on another experience where he made a mistake when working with a student in a separate reflection journal entry.

> *[My biggest challenge was that] I made a mistake during one of my lessons and I felt like the dynamic between me and the students I was helping changed for the worse. I thought they were seeing me as inferior which was a complete exaggeration. [This was a challenge because] I was constantly putting myself down and not realizing that it's okay to not know how to do something. Presenting things to the class can sometimes lead me down this road. I don't intentionally mess up, but a mistake will slip and my peers will catch it and question me which makes my dynamic with them, on my part, super weird.* [Sidney, Reflective Journal Week 6, Waves and Vibrations]

Sidney continues to grapple with the purpose and goal of facilitating discussion. Concerns over having the right answer highlight the importance of content proficiency for effective teaching and are consistent with *absolute* ways of knowing. But this experience also set the stage for some deeper reflection. In a follow-up interview, Sidney elaborated on these experiences and how they changed his beliefs about teaching, learning, and his role in facilitating learning. The following excerpt illustrates how the banking model and notions of authority were disrupted by his LA experience.

> *[My approach as an LA shifted] because I didn't view the LA role as what I should have. I definitely viewed myself as putting myself in a teacher position. And I didn't recognize the fact that I, myself, am a student and*

[1]Important to note about this experience is that other LAs also got things wrong in class and revised their beliefs about the importance of content knowledge and authority in the classroom. We chose to highlight Sidney in particular because of the detail they offer in their experience and the evident dissonance and resulting epistemological growth.

that I'm not there to necessarily be a power figure—but there to be supportive and to assist them to my capacity. And so having the right answer was important for my ego specifically. I felt like I needed to be able to impress the students even though I'm not a teacher. And so that was very important. And then that moment where I made a mistake, that Snell's law moment, that really broke down from there. And then I was like, "Okay. Crap. I'm just going to start telling them when I don't know things and not pretend like I'm some power figure in this room." [Sidney, Follow-up Interview, Waves and Vibrations]

Here, his focus explicitly shifts from needing to be correct and authoritative to recognizing his role as "supporting and assisting" student learning. He notes how being right was mostly about him and his ego and how being wrong about an answer or not knowing something helped him revise his understanding of his goals. This change is noteworthy because it represents a fundamental shift in the ways LAs make sense of educational contexts and signifies a move from a banking model of education (i.e., absolute) to a stance that recognizes the importance of co-creation of knowledge and of sharing understanding (i.e., transitional).

Another LA articulated a similar shift in his belief about his role, and he also seemed to struggle with fully committing to a new stance. While mental models are typically addressed from the point of view of trying to understand the *student's* mental model, Taylor uses that same concept to describe their own growth and epistemological development.

I think on a more objective level, just being more prepared if I had gone through the worksheet and just like looked at, "Okay, what questions might I be able to anticipate from students?" But that's not the best way to do it. I'd say I could have—I think there is a piece of me that needs to unlearn a lot of what I think teaching is. I mean, not even teaching, like LAing (sic). Because in seminar, you learn […] you're not answering questions, you're just redirecting the student to go down the line of thinking that's going to be most beneficial for them, or you're trying to send a student down a path that's going to reshape their mental model of how they understand this physics concept. [Taylor, Follow-up Interview, Physics for STEM Majors]

Here, Taylor describes how he has interpreted the goals of the program as discussed in the LA pedagogy seminar and how it has prompted him to confront his existing epistemological beliefs ("I think there is a piece of me that needs to unlearn a lot of what I think teaching is"). Taylor continues to discuss his internal, unlearning process:

I think if I could really wrap my head around that and just truly accept that, but it's not like I don't believe it. But it goes against my mental model of what teaching is or what being an LA is. But I think […] truly knowing that that's what being an LA is, and understanding that, and being able to incorporate that into how I LA, would boost that confidence and like enable a more appropriate delivery of some questions. So even if I didn't know something, I could be confident in the fact that that's irrelevant, because I can still ask questions that are going to put the student on the right track. [Taylor, Follow-up Interview, Physics for STEM Majors]

Taylor recognizes shifts in his own beliefs about facilitating learning, but also notes how this shift has been difficult to internalize ("if I could really wrap my head around that and just truly accept that"). Taylor seems like he accepts, or could accept, beliefs related to more transitional epistemologies, suggesting, at the very least, an awareness of other ways of knowing and reasoning. However, he is not ready to fully embrace it himself ("But it goes against my mental model of…what being an LA is).

As LAs worked through challenges related to being "wrong," these experiences seemed to create space for them to revise their epistemological beliefs about teaching and learning. Specifically, they shifted from an emphasis on authority and possession of knowledge to an emphasis on soliciting student understanding and co-constructing knowledge.

D. Summary of results

Over the course of an academic quarter (10 weeks), LAs noted different kinds of experiences and challenges that seemed to create the space for reflection and growth. First, miscommunication issues helped LAs recognize the role and importance of language in learning and conceptual understanding. Second, by witnessing professors struggle with challenging content or questions, LAs in this study began to think more about the humanistic aspects of learning and how to validate struggling students. Finally, by giving students the "wrong" answer, LAs revised their beliefs about how to meaningfully facilitate learning and began the develop approaches for co-constructing knowledge alongside students. These experiences posed challenges for LAs, but also offered a concrete way for LAs to critically reexamine their epistemological beliefs across domains.

What is notable about these experiences is that they occurred during authentic interactions that might not be available to all LAs in a given academic term. That is, these impactful experiences outlined above are sporadic and unplanned. However, given the power of these experiences and the ways they might facilitate critical epistemological growth, it seems important that educators consider how to provide experiences for all LAs in ways that are equitable and that intentionally promote that growth.

V. DISCUSSION AND IMPLICATIONS

Taken together, our findings suggest that educators interested in training LAs may consider creating intentionally designed learning spaces for LAs that are unique to their role in classroom contexts. We address this topic in three ways. First, we use the concept of *learning to listen* to highlight how educators should work to create space for these experiences during training and preparation. Second, given the ways that LAs interact with instructors to prepare for class, faculty should consider concepts related to legitimate peripheral participation and cognitive apprenticeship to inform their interactions with LAs. Finally, given that most LAs, at least in this study, seem to operate from an *absolute* or *transitional* way of knowing and reasoning, it is vital that LA training meet students at the appropriate epistemological level and scaffolds epistemological development in ways that validate LAs and encourage growth.

A. Learning to listen as a means for epistemological growth

Overall, our findings suggest that LA experiences can be a means to promote epistemological development for those who participate in the program. This is noteworthy because some of the experiences described in the results seem to be unique to the LA program itself and arise out of the experiences and interactions the LA model seems to promote. For example, recognizing the importance of language for learning helped LAs confront, examine, and reorient to their beliefs about teaching and learning and understanding. Many LAs began the program with beliefs about knowledge and learning that positioned knowledge as a substance stored in and disseminated by authority figures which were often the professors or themselves as LAs. In this view, learning occurs when the experts give knowledge to students and communication is unidirectional. However, as LAs moved through the program and gained classroom experience, they came to see learning as more relational and emphasized the interpersonal, bidirectional nature of communication. For LAs who made this shift, communication between educator and student came to flow in both directions, and the ability to listen to students and understand their language became an important way to facilitate learning.

While communication is often noted as a vital skill in STEM disciplines [31–34], teaching related to those skills often emphasizes skills related to clearly *explaining* a topic to someone (e.g., Ref. [35]). And while developing concise, coherent explanations is important, this emphasis can cause educators to overlook the dialectic nature of learning and the importance of listening for scaffolding student understanding. One way to address communication skills is through techniques such as active listening [36,37]. Active listening involves communication practices such as paraphrasing, making empathic comments, asking questions for verification. The goal of active listening is to ensure mutual understanding and to accurately discern the meanings and intentions of the speaker. Given the goals of the LA program broadly and those of active listening in particular, it seems important that LA training and preparation address these concepts and provide opportunities to practice the associated techniques. Researchers in teacher education have noted how active listening can improve interpersonal interactions [38], and these techniques might also benefit LAs in STEM classrooms. For example, LA seminars might include opportunities for LAs to share impactful classroom experiences and for others to engage in some of the practices related to active listening. Further, LA training might leverage the mixed-reality framework developed by Ref. [10] to offer LAs a low-stakes environment in which to practice these skills. These processes can develop LA skills related to listening and help LAs see how they might apply them to classroom situations.

B. Situated learning and legitimate peripheral participation

As LAs move through the program and the academic term, they developed a deeper understanding of their role in the classroom and the ways they were able to facilitate student learning. This deepening in understanding resembles the processes laid out by Lave and Wenger [14], who describe learning as taking place through enculturation into a community of practice. In situated learning, novices begin on the boundaries of a given practice and, over time, become more central to practice and become more *situated* within that community. Critical to this enculturation is the guidance and feedback from more experienced, knowledgeable members of the community in the form of mentors and experts. Learning in this way resembles a process of apprenticeship as novices learn the content and context of fuller participation in a community.

The situated view of learning advanced by Lave and Wenger and others can inform two critical elements of LA preparation, training, and professional development. First, the apprenticeship model has the potential to help LAs better enact particular pedagogical techniques. Faculty can engage in effective teaching practices and student interactions in ways that model the kinds of behaviors they want from their LAs. For instance, faculty can engage in a Socratic dialogue with students to demonstrate effective questioning practices that guide students to their own understanding and can help LAs understand the tactics they engage in and why they use them. Faculty and LA pedagogy instructors can leverage concepts from cognitive apprenticeship (e.g., Refs. [39,40]) to help clarify what they want from LAs as well as why they want to encourage particular behaviors and interactions. By being intentional about the goals of the LA model and transparent about desired student outcomes, faculty can help LAs develop

pedagogical techniques that are effective within their classroom contexts in ways that make them more effective in facilitating student learning. Mentors can help students move beyond seeing specific techniques as merely "teaching tips" and help them better understand the underlying motivations and theories behind these techniques.

Second, the apprenticeship model noted by Lave and Wenger emphasizes the integration of members into relevant communities of practice. The LA model can therefore help integrate the LAs into a broader community of STEM educators. Faculty can do this by providing space for LAs to practice particular techniques in their classrooms (e.g., metacognitive questioning) and helping LAs recognize these practices as vital to the broader goals of promoting student learning and conceptual understanding. Helping LAs see themselves as *legitimate* STEM educators can encourage them to pursue careers in STEM education. Prior research [8] illustrates how LAs come to participate as members of a community of practice and take on identities as STEM educators, and attention to apprenticeship models of development can encourage this kind of enculturation and membership. Given that one of the goals of the LA model is to promote entrance into STEM education disciplines, faculty can play a critical role in helping to cultivate a new generation of enthusiastic educators with a strong foundation in active learning and constructivist pedagogies. By applying principles from legitimate peripheral participation as well as cognitive apprenticeship, faculty can improve LA pedagogy and help LAs develop a stronger identity as STEM educators.

C. Limitations

The research should be interpreted considering existing limitations. First, while we observed some epistemological growth, examination, and reorientation, it was not uniformly observed across domains. Therefore, while we demonstrate shifts in perspectives on teaching and learning and knowledge, most LAs still primarily operate from an absolute way of knowing. However, it is important to note that most LAs in this study were in their 2nd or 3rd year in college, and such results are consistent with Baxter Magolda's findings in which she demonstrated that most college students do not progress to independent or contextual knowing until at least their final year of college. Therefore, while our results do not offer a view of the full range of ways of knowing and reasoning, they are nonetheless consistent with existing research on epistemological development. Another limitation concerns the relatively short time span of data collection for any single participant. Although the collection protocols produced, rich qualitative data, they occur over a 10-week period, which presents challenges for fully capturing epistemological development. It is possible that LAs' epistemologies continued to shift beyond the 10-week quarter as a result of their experiences, but our methods used here cannot observe shifts in other domains or changes in ways of knowing. Indeed, future research should examine the longer-term impacts of participation in LA programs and potential latent effects on epistemological growth.

Further, some LAs did not provide complete reflection data. Because the reflections were made to capture single events, it is therefore possible that we do not have complete data on all impactful experiences. Nonetheless, follow-up interviews afforded the research team the ability to ask about specific events which helped to mitigate these issues. Finally, the data collection occurred both before and during the COVID-19 pandemic. As a result, there is a mix of both in-person interviews and virtual videoconference interviews. Relatedly, some LAs worked in in-person classes while others facilitated learning in online courses, and some participants have experience in both modalities. While we did not emphasize the change or influence of virtual learning in the interviews, this change in modality did influence how LAs worked and interacted with students and faculty.

Finally, our dataset and conclusions are limited because the study was conducted at a predominantly white institution (PWI). Recently, Kanim and Cid reported that physics education research studies are not representative of the average US-based physics students [41]. It stands to reason that our LAs are supporting courses that are similarly not representative of an average student, and thus our conclusions are limited. Further, since our study unpacks LAs' ideas on how knowledge is constructed, it is important to capture diverse viewpoints and ways of knowing. To address this issue, we are continuing our research at community colleges.

VI. CONCLUSION

LAs serve an important role in STEM education settings. And as their prevalence grows in these spaces and LA programs expand and begin at other universities, it is important that stakeholders in LA training, preparation, and success are thoughtful about the kinds of opportunities they can provide. Our findings suggest that attention to epistemological growth can improve training and preparation efforts for LA programs and, ultimately, student learning in the classes they support. Further, we argue that certain kinds of experiences and challenges can create the dissonance and reflective space needed to promote epistemological growth. Our data highlight the importance of language in learning and demonstrate the ways that individuals in traditional authority positions (e.g., instructors, LA seminar faculty) can serve as models for productive struggle and create spaces for collaborative learning. While these experiences noted in the current paper are impactful for some LAs, these challenges occurred organically and without *a priori* goals or outcomes. That is, not everyone in the cohorts studied here had access to these kinds of experiences that were instrumental in

fostering epistemological development. A challenge therefore remains for educators regarding how to create spaces for LAs that can foster this growth in more intentional and equitable ways such that all LAs have access to these impactful experiences. While not all LAs experience these personal evolutions, concepts related to situated learning offer a useful mechanism to provide space for learning and conversations needed to both promote LA epistemological growth and support student learning.

Finally, we contemplate the role of the LA pedagogy seminar within the context of our institutional and student context. Over three-fourths of our LAs during this study were engineering majors, with the remaining fourth in physics and astronomy. Of all the LAs in this study, only 1–2 indicated a desire to pursue a teaching-focused career. Instead, they cited their interest in the LA program as rooted in appreciation of the course content, a willingness and desire to "help" fellow students, and a sense of community with other LAs. While there are numerous studies outlining the effect of explicit instruction on epistemology for pre- and in-service teachers (e.g., Refs. [42–45]), we wish to pose a complementary question: What is the implication of LA programs for preparing epistemologically sophisticated *physicists and engineers*? What could we expect if our burgeoning scientists have an education which includes a space to embrace a mindset wherein knowledge is collaboratively constructed, and everyone engaged in the endeavor is capable of both teaching and learning? We contemplate, and invite the reader to contemplate, a future where engineers and scientists might come to see questions as sources of knowledge and how it might impact the way we, as a society, approach science.

ACKNOWLEDGMENTS

This material is based in part upon work supported by the California Learning Lab. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the California Learning Lab. We are also grateful for the insight provided by our participants and the contributions they made to the study and the insights they shared. These perspectives were invaluable to the research project and have been instrumental in developing our findings. L. R. also thanks Gina Quan, Cassandra Paul, Jennifer Avena, Kim Coble, and Resa Kelly for productive discussions on LA epistemological development.

APPENDIX A: OPERATIONALIZED CODEBOOK

Baxter Magolda's epistemological reflection model consists of two broad constructs: *ways of knowing* and *domains*.

Ways of knowing describes stages of epistemological trajectory. *Domains* describes the role of a particular participant in the learning process. These constructs are necessarily orthogonal, as described in the original work by Baxter Magolda. As discussed in the paper in Sec. II (Theoretical Framework), this leads to two important implications for analysis of the data:

(1) When students describe their beliefs, they do so at the intersection of ways of knowing and domains. Thus, we must code in both ways of knowing and domain for a given utterance.
(2) As students develop epistemologically, the preponderance of one way of knowing over others does tend to emerge as the dominant pattern for a time. For this work, this means that participants in this study were not labeled as one kind of knower or another. Rather, individual units of analysis (discussed below) were examined at the aggregate level to explore patterns across participants and over time.

In this Appendix, we provide additional details for the interested reader on Baxter Magolda's framework itself and its application in this work. Finally, we show a co-occurrence matrix for informational purposes in Table VI.

1. Epistemological reflection model additional details

Table I in the main text describes *ways of knowing* and *domains* as conceptualized in Ref. [18], and interpreted by Lutz and Ríos for this context [21]. Only two ways of knowing are described in the main work: absolute and transitional. This is because we predominantly coded in these two ways of knowing.

As noted, these constructs are orthogonal; we present each construct at a time here for clarity and to further describe the coding process. We also included the independent and contextual ways of knowing for the interested reader.

In Table IV, it is important to note that the "nature of knowledge" domain is as written in the original work by Baxter Magolda, and is mostly about how certain or uncertain a participant believes knowledge is. Most definitions of epistemology include language related to, for instance, ideas, conceptions, and beliefs about the *nature*, source, and justification of knowledge. Thus, including a domain entitled, nature of knowledge might initially be confusing. We did not want to change this in order to remain aligned with Baxter Magolda's framework. For the reader, it is sufficient to know that the nature of knowledge domain does not refer to epistemology broadly. It refers to the participants' ideas about how certain knowledge is.

In addition to domains, Baxter Magolda describes four developmental stages of epistemological reflection (way of knowing): absolute, transitional, independent, and contextual.

2. Code application

Finally, we show a co-occurrence matrix for informational purposes. These codes were computed after all rater negotiation, across the entire data set (pre and post interviews and reflective journals). Units of analysis could be coded according to multiple domains at one time

TABLE IV. Overview of domains within the epistemological reflection model.

Domain	Operational definition
Role of the Learner	Participant describes behaviors, ideas, and standards learners (i.e., students) need to have to demonstrate knowledge or understanding of a topic. Coded when LAs refer to the students in the classroom where they work, and what/how they should behave and think in the learning process
Role of the Instructor	Participant describes behaviors and standards of instructors in defining and disseminating knowledge. Coded when LAs refer to the instructors in the class they work with, and what/how they should behave and think in the learning process
Role of peers	Participant describes the behaviors, ideas, and standards of peer groups in acquiring and sharing knowledge. Coded when LAs refer to students working with one another in the class they work with, and what/how they should behave and think in the learning process. (Not coded when LAs refer to themselves as peers, e.g., in a different class where they are currently students.)
Evaluation	Participant describes beliefs about how individuals know things or how understanding of something might be assessed. Coded when LAs refer to ways of justifying or proving understanding of topics, for any person. These usually entail attitudes towards common classroom assessment such as quizzes or exams. This may be co-coded with any of the roles above if the LA mentions evaluation for a certain actor (e.g., students' approach to quizzes versus instructors' approaches).
Nature of knowledge	Participant describes beliefs about the certainty with which something can be known as well as the sources of authority regarding who is knowledgeable. Coded when LAs refer to the tools, standards, and notions they employ to differentiate between knowing and not knowing an idea, topic, or problem.
Role of learning assistant[a]	Participant describes the behaviors, ideas, and standards of LAs. Coded when LAs refer to their own beliefs about their role in the classroom or the role of other LAs. Maybe be generalized or idealized thoughts about the role of LAs in the learning process (e.g., the LAs' purpose is to facilitate discussion amongst peers).

[a]This is an extension to the Baxter Magolda epistemological reflection model for the context of our work.

TABLE V. Overview of the different ways of knowing described in the epistemological reflection model.

Way of knowing	Operational definition
Absolute	Beliefs that knowledge is certain and that absolute answers exist in all areas of knowledge. This knowledge is possessed by instructors and transmitted primarily in the form of lectures. Everything is knowable; the limitation rests on the learner's lack of information. Learning entails obtaining this knowledge and storing it for subsequent reproduction of knowledge. Knowledge is absolute and needs to be obtained from experts. Knowledge is evaluated on the basis of correctness based on expert review. Any difference in explanation is due to preferences or language disagreements, not indicative of any inherent uncertainty in knowledge. Coded when the participant expresses a belief, notion, idea, or conception reflecting the above description.
Transitional	Beliefs that some knowledge is uncertain in some areas and that some questions do not have exact answers. Knowledge is something that is understood (rather than stored or collected), and instructors should facilitate learning that promotes conceptual understanding and application of topics. Learners should understand the practical application of knowledge. Debate does not indicate inherent uncertainty in knowledge *per se*, but in different perspectives on the same, objective stance or issue. Coded when the participant expresses a belief, notion, idea, or conception reflecting the above description.
Independent[a]	Beliefs that most knowledge is uncertain and that most things are not knowable, but more a matter of opinion or personal experiences. Knowledge no longer resides in authority figures and many different opinions and ideas are considered valid. Learning emphasizes constructing one's own viewpoint and hearing those of other learners. Coded when the participant expresses a belief, notion, idea, or conception reflecting the above description.

(Table continued)

TABLE V. *(Continued)*

Way of knowing	Operational definition
Contextual[b]	Beliefs that knowledge is tentative, negotiated, and valid within appropriate contexts. Claims about knowledge must be supported by evidence and authority about knowledge is evaluated in light of relevant elements of a given situation. Learning should be viewed as the application of skills within contexts and involve opportunities for reflection and critique from both instructors and peers. Coded when the participant expresses a belief, notion, idea, or conception reflecting the above description.

[a]There was 1 utterance coded under this way of knowing.
[b]There were no utterances coded under the contextual way of knowing. This result maps onto Baxter Magolda's work, which indicated that exceptional few college-age student espouse contextual views or perspectives.

TABLE VI. Overview of the different ways of knowing described in the epistemological reflection model.

	Way of knowing	
Domain	Absolute	Transitional
Role of learner	136	120
Role of peer	19	24
Role of instructor	30	12
Evaluation	57	8
Nature of knowledge	58	20
Role of LA	311	192

(e.g., could be coded as both role of learner and evaluation) and so the totals below not necessarily represent the number of coded segments overall. Further, the prevalence of any particular code is the result of a combination of a number of different factors, including the interview protocol as well as the particular direction of a given semi-structured interview, and so frequency counts should not necessarily be understood as a measure of the salience of a given domain.

APPENDIX B: RESEARCH PROTOCOLS

1. Beginning-of-quarter interview protocol

1. Think about a concept you understand well.
   a. How did you come to understand it?
   b. How do you know you understand it?
   c. How would you prove that understanding to someone else?
2. Why is understanding mechanics concepts important for you personally as a student?
3. Why is understanding mechanics concepts important for [other physicists, other engineers, other students]?
4. How important is it for individuals outside of your discipline to understand mechanics concepts?
5. When you are trying to communicate a complicated concept to someone else, can you describe your typical approach? What are some things you do or say?
6. When do you think learning happens most effectively for students?
7. When are you most effective as an LA?
8. How does your thinking process or approach in STEM classes differ from the way you think and approach problems in your non-STEM courses?

2. End-of-quarter interview protocol

1. Can you tell me about a time this quarter where you felt learning went exceptionally well?
   a. What do you think made it go so well?
   b. How did you know it was going well?
   c. What evidence were you working with?
2. Alternately, can you tell me about a time during the quarter where learning maybe did not go so well?
   a. In your opinion, why did it not go well?
   b. Was there anything that could have been done to improve it? What would that be?
3. How has your understanding of engineering mechanics changed throughout the course?
4. How has teaching mechanics influenced the way you understand the same concepts?
5. When do you think learning happens most effectively for students?
6. When are you most effective as an LA?
7. I'd like to talk a little more about this particular reflective journal entry. It seems like that was a particularly impactful time for you. Can you talk a little about what was going on during that time?

3. Reflective journal prompts

1. As a LA, what was your biggest challenge over the last two weeks?
2. What made it so challenging?
3. Have you ever encountered this challenge before? Where?
4. Did anyone help you with this challenge?
5. Who helped you with this challenge?
6. What would you do differently the next time you encounter this challenge?
7. How has this challenge influenced your learning and approach as an LA?

[1] A. P. Barrasso and K. E. Spilios, A scoping review of literature assessing the impact of the learning assistant model, Int. J. STEM Educ. **8**, 12 (2021).

[2] E. W. Close, J. Conn, and H. G. Close, Becoming physics people: Development of integrated physics identity through the Learning Assistant experience, Phys. Rev. Phys. Educ. Res. **12**, 0010109 (2016).

[3] S. J. Pollock and N. D. Finkelstein, Sustaining educational reforms in introductory physics, Phys. Rev. Phys. Educ. Res. **4**, 010110 (2008).

[4] J. L. Alzen, L. S. Langdon, and V. K. Otero, A logistic regression investigation of the relationship between the Learning Assistant model and failure rates in introductory STEM courses, Int. J. STEM Educ. **5**, 56 (2018).

[5] N. Sellami, S. Shaked, F. A. Laski, K. M. Eagan, and E. R. Sanders, Implementation of a learning assistant program improves student performance on higher-order assessments, CBE Life Sci. Educ. **16**, ar62 (2017).

[6] D. Caravez, A. De La Torre, J. Nissen, and B. Van Dusen, Longitudinal associations between learning assistants and instructor effectiveness, arXiv:1711.05834.

[7] V. Otero, S. Pollock, and N. Finkelstein, A physics department's role in preparing physics teachers: The Colorado Learning Assistant Model, Am. J. Phys. **78**, 1218 (2010).

[8] E. W. Close, J. Conn, and H. G. Close, Learning assistants' development of physics (teacher) identity, in *Proceedings of PER Conf. 2013, AIP, Portland, OR*, 10.1119/perc.2013.pr.010.

[9] P. C. Hamerski, P. W. Irving, and D. McPadden, Learning assistants as student partners in introductory physics, Phys. Rev. Phys. Educ. Res. **17**, 020107 (2021).

[10] J. J. Chini, C. L. Straub, and K. H. Thomas, Learning from avatars: Learning assistants practice physics pedagogy in a classroom simulator, Phys. Rev. Phys. Educ. Res. **12**, 010117 (2016).

[11] K. E. Gray, D. C. Webb, and V. K. Otero, Effects of the learning assistant model on teacher practice, Phys. Rev. Phys. Educ. Res. **12**, 020126 (2016).

[12] L. Ding and P. Zhang, Making of epistemologically sophisticated physics teachers: A cross-sequential study of epistemological progression from preservice to in-service teachers, Phys. Rev. Phys. Educ. Res. **12**, 020137 (2016).

[13] J. S. Brown, A. Collins, and P. Duguid, Situated cognition and the culture of learning, Educ. Res. **18**, 32 (1989).

[14] J. Lave and E. Wegner, *Situated Learning: Legitimate Peripheral Participation* (Cambridge University Press, Cambridge, England, 1991).

[15] B. D. Lutz, S. A. Brown, and N. Perova, Exploring practicing engineers' understanding of fluid mechanics concepts, Int. J. Eng. Educ. **35**, 535 (2019).

[16] S. Brown, B. Lutz, N. Perova-Mello, and O. Ha, Exploring differences in statics concept inventory scores among students and practitioners, J. Eng. Educ. **108**, 119 (2019).

[17] C. Krist, Examining how classroom communities developed practice-based epistemologies for science through analysis of longitudinal video data, J. Educ. Psychol. **112**, 420 (2020).

[18] M. B. B. Magolda, *Knowing and Reasoning in College: Gender-Related Patterns in Students' Intellectual Development* (Jossey-Bass, New York, 1992).

[19] W. G. Perry Jr., *Forms of Intellectual and Ethical Development in the College Years: A Scheme*, Jossey-Bass Higher and Adult Education Series (Jossey-Bass Publishers, San Francisco, CA, 1970).

[20] M. B. B. Magolda, Post-college experiences and epistemology, Rev. High. Educ. **18**, 25 (1994).

[21] L. Ríos and B. Lutz, Operationalizing the orthogonal role of a learning assistant in the classroom to analyze epistemological development, in *Proceedings of the American Society for Engineering Education Annual Conference & Exposition, Minneapolis, MN* (2022), https://peer.asee.org/40939.

[22] B. D. Lutz and M. C. Paretti, Exploring school-to-work transitions through reflective journaling, in *Proceedings of the American Society for Engineering Education Annual Conference & Exposition, Columbus, Ohio* (2017), 10.18260/1-2–28332.

[23] M. T. H. Chi, P. J. Feltovich, and R. Glaser, Categorization and representation of physics problems by experts and novices, Cogn. Sci. **5**, 121 (1981).

[24] M. B. B. Magolda, The activity of meaning making: A holistic perspective on college student development, J. Coll. Student Dev. **50**, 621 (2009).

[25] J. L. Campbell, C. Quincy, J. Osserman, and O. K. Pedersen, Coding in-depth semistructured interviews: Problems of unitization and intercoder reliability and agreement, Sociol. Methods Res. **42**, 294 (2013).

[26] J. Saldaña, *The Coding Manual for Qualitative Researchers* (Sage, Thousand Oaks, CA, 2015).

[27] M. Carcary, The research audit trial—enhancing trustworthiness in qualitative inquiry, Electron. J. Bus. Res. Methods **7**, 11 (2009).

[28] D. Hammer and A. Elby, Tapping epistemological resources for learning physics, J. Learn. Sci. **12**, 53 (2003).

[29] P. Freire, *Pedagogy of the Oppressed* (Bloomsbury Publishing, New York, 2018).

[30] M. T. H. Chi, Laboratory methods for assessing experts' and novices' knowledge, Cambridge Handb. Expert. Expert Perform., 167 (2006).

[31] M. C. Paretti, Teaching communication in capstone design: The role of the instructor in situated learning, J. Eng. Educ. **97**, 491 (2008).

[32] A. Pfluger, M. Armstrong, T. Corrigan, E. Nagelli, C. James, A. Miller, and A. Biaglow, Framework for analyzing placement of and identifying opportunities for improving technical communication in a chemical engineering curriculum, Educ. Chem. Eng. **31**, 11 (2020).

[33] M. C. Paretti, Audience awareness: Leveraging problem-based learning to teach workplace communication practice, IEEE Trans. Prof. Commun. **49**, 189 (2006).

[34] J. Trevelyan, *The Making of an Expert Engineer* (CRC Press, Boca Raton, 2019).

[35] S. Ruff and M. Carter, Communication learning outcomes from software engineering professionals: A basis for teaching communication in the engineering curriculum, in *Proceedings of the 2009 39th IEEE Frontiers in Education Conference, San Antonio, TX, 2009* (IEEE, 2009), pp. 1–6, 10.1109/FIE.2009.5350442.

[36] H. Weger Jr., G. Castle Bell, E. M. Minei, and M. C. Robinson, The relative effectiveness of active listening in initial interactions, Int. J. List. **28**, 13 (2014).

[37] J. A. Leydens and J. C. Lucena, Listening as a missing dimension in engineering education: Implications for sustainable community development efforts, IEEE Trans. Prof. Commun. **52**, 359 (2009).

[38] D. McNaughton, D. Hamlin, J. McCarthy, D. Head-Reeves, and M. Schreiner, Learning to listen: Teaching an active listening strategy to preservice education professionals, Topics Early Child. Spec. Educ. **27**, 223 (2008).

[39] A. Collins, J. S. Brown, and A. Holum, Cognitive apprenticeship: Making thinking visible, Am. Educat. **15**, 6 (1991).

[40] J. S. Brown, A. Collins, and S. E. Newman, Cognitive apprenticeship: Teaching the crafts of reading, writing, and mathematics, *Knowing, Learning, and Instruction: Essays in Honor of Robert Glaser* (1989).

[41] S. Kanim and X. C. Cid, Demographics of physics education research, Phys. Rev. Phys. Educ. Res. **16**, 0020106 (2020).

[42] K. B. Wendell, J. E. S. Swenson, and T. S. Dalvi, Epistemological framing and novice elementary teachers' approaches to learning and teaching engineering design, J. Res. Sci. Teach. **56**, 956 (2019).

[43] J. A. Greene and S. B. Yu, Educating critical thinkers: The role of epistemic cognition, Policy Insights from Behav. Brain Sci. **3**, 45 (2016).

[44] E. Scanlon, What is epistemology and why should you care?, Bull. Am. Phys. Soc. 60 (2015), http://meetings.aps.org/link/BAPS.2015.TSS.F1.2.

[45] E. Scanlon, J. Schreffler, W. James, E. Vasquez, and J. J. Chini, Postsecondary physics curricula and Universal Design for Learning: Planning for diverse learners, Phys. Rev. Phys. Educ. Res. **14**, 020101 (2018).