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Preservice elementary teachers' perceptions of their science laboratory instructors in a phenomena-based laboratory and how it impacts their conceptual development

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Abstract

Phenomena-based approaches have become popular for elementary school teachers to engage children's innate curiosity in the natural world. However, integrating such phenomena-based approaches in existing science courses within teacher education programs present potential challenges for both preservice elementary teachers (PSETs) and for laboratory instructors, both of whom may have had limited opportunities to learn or teach science within the student and instructor roles inherent within these approaches. This study uses a convergent parallel mixed-methods approach to investigate PSETs' perceptions of their laboratory instructor's role within a Physical Science phenomena-based laboratory curriculum and how it impacts their conceptual development (2 instructors/121 students). We also examine how the two laboratory instructors' discursive moves within the laboratory align with their's and PSETs' perceptions of the instructor role. Qualitative data includes triangulation between a student questionnaire, an instructor questionnaire, and video classroom observations, while quantitative data includes a nine-item open response pre-/post-semester conceptual test. Guided by Mortimer's and Scott's analytic framework, our findings show that students primarily perceive their instructors as a guide/facilitator or an authoritarian/evaluator. Using Linn's knowledge integration framework, analysis of pre-/post-tests indicates that student outcomes align with students' perceptions of their instructors, with students who perceive their instructor as a guide/facilitator having significantly better pre-/post-outcomes. Additional analysis of scientific discourse from the classroom observations illustrates how one instructor primarily supports PSETs' perspectives on authentic science learning through dialogic–interactive talk moves whereas the other instructor epistemologically stifles personally relevant investigations with authoritative–interactive or authoritative–noninteractive discourse moves. Overall, this study concludes by discussing challenges facing laboratory instructors that need careful consideration for phenomena-based approaches.

KEYWORDS

instructor guidance, knowledge integration, science explanations, teacher education

1 | INTRODUCTION

Phenomena-based approaches are gaining increasing popularity, as reflected in many exciting lines of research including practice-based teacher education, science practices engagement, ambitious science teaching, and so forth (Davis & Palincsar, 2023; Reiser et al., 2021; Windschitl et al., 2018). Phenomena-based instruction lacks a universal definition, but common characteristics include (1) engaging learners in science with a caring community, (2) orienting student-led investigations in phenomena-based contexts, (3) providing metacognitive support in refining explanations and solutions, and (4) allowing instructors and students to learn with and from each other (National Academies of Sciences, Engineering, and Medicine (NASEM), 2021). Many science content courses within teacher preparation programs, typically led by science departments as opposed to education departments, struggle to incorporate such features into classroom practice (Loverude et al., 2011; Robertson et al., 2019). The lack of phenomena-based approaches (eliciting prior ideas, engaging in sensemaking, supporting uncertainty, etc.) in teacher preparation science courses has implications for future K-12 classrooms, due in part because PSETs often teach science as it was modeled during their learning experiences (Alsahou & Alsammari, 2019; Jaber, 2021; Lowell et al., 2021; Tekkumru-Kisa & Stein, 2015).

Integration of phenomena-based instruction into teacher education science courses creates a shift in the locus of control allowing PSETs to become epistemic agents (Fang et al., 2019; Lowell et al., 2021; Miller et al., 2018). Epistemic agents assume the responsibility to think for themselves and influence social standards within a classroom community (Stroupe, 2014). Considering how PSETs adopt unfamiliar roles as epistemic agents, laboratory instructors need to facilitate supportive discussions that encourage knowledge construction (Donnelly et al., 2016; Kawasaki & Sandoval, 2019). Such shifts are promising considering a large-scale, randomized-cluster experimental design study that reveals how student-centered approaches lead to stronger understanding of explanatory models relative to teacher-centered approaches (Granger et al., 2012). Further, results suggest that conceptual outcomes improve when learners perceive their instructors as a facilitator (Wheeler et al., 2019). Given how instructors need to strike a balance between providing guidance and supporting ownership, "What characterizes effective guidance?", remains a widely debated topic (Zhang & Cobern, 2021, p. 210).

This study investigates how university laboratory instructors support PSETs' scientific investigations during Physical Science laboratory instruction. To the best of our knowledge, few to no studies provide insight into challenges university laboratory instructors experience when supporting PSETs in phenomena-based learning environments. Further, this study addresses concerns regarding how "there have not been studies that lend themselves to develop broader and shared understandings of learning in STEM teacher preparation" (Bell et al., 2019, p. 24). In turn, the following research questions guide this study.

1. Whether and to what extent are PSETs' perceptions of their instructor's role associated with their pre-/post-conceptual development?
2. Whether and to what extent do laboratory discursive interactions align with PSET and instructor perceptions of the instructor role?

2 | LITERATURE REVIEW

2.1 | Engaging future teachers in science with a caring community

Considering how PSETs interact with university laboratory instructors more than faculty, it is important to clarify how future teachers and scientists work together during phenomena-based investigations (Wheeler et al., 2017b). Research indicates how division in scientific expertise between scientists such as university laboratory instructors and K-12 teachers create social environments that hold a scientist's knowledge and values in high regard while undermining the funds of knowledge possessed by PSETs (González & Moll, 2002; Shanahan & Bechtel, 2020; Tanner et al., 2003). Such unbalanced power dynamics create epistemic injustice within the classroom by restricting science learning to situations in which PSETs take on a diminished role within the classroom, passively listening to the instructor (Donnelly et al., 2014).

Finne et al. (2022) interviewed students about the role of instructors during laboratory instruction. Results indicate how students recognize that their knowledge construction is mediated by an instructor's willingness to provide guidance during student-led investigations. Further, Kendall and Schussler (2013) reveal how perceptions of an instructor are significantly associated with students' perceptions of their own learning outcomes. Therefore, university laboratory instructors play a key role in facilitating knowledge construction through instructor–student interactions (Agustian et al., 2022). Without instructor guidance, students "may not know what they do not know, what they do know, and what tasks they need to complete" (Chen, 2022, p. 415).

Thus, science courses for PSETs need to provide inclusive and welcoming spaces, valuing all voices, and need to recognize the critical role future elementary teachers can and should play in the advancement of STEM disciplines. Jaber et al. (2018) delineate how "epistemic empathy" can be promoted within learning environments, "to make space for all voices, and to shield students from negative emotions" (p. 13). Epistemic empathy refers to when an instructor demonstrates an appreciation and develops an understanding of learners' cognitive and emotional experiences during social exchanges that motivate the construction and revision of scientific explanations (Jaber et al., 2018).

Although prior research focuses on building epistemic empathy for K-12 students, we suggest that laboratory instructors need to display epistemic empathy for PSETs, especially due to the division in scientific expertise between scientists and future teacher candidates (Shanahan & Bechtel, 2020). Thus, if learning environments are designed to engage PSETs in, "experiencing the feelings of excitement, frustration, and vulnerability of doing science", then laboratory instructors need to cultivate a supportive classroom environment and promote PSETs' ownership in learning science (Jaber et al., 2022, p. 246). As such, laboratory instructors within this study have a critical role in (1) noticing and appreciating PSETs' emotions, (2) recognizing the underlying reasoning for PSETs' ideas, (3) finding merit in PSETs' ideas, (4) anticipating PSETs' ideas, (5) noticing patterns and shifts in how PSETs engage in scientific reasoning, (6) expressing curiosity in PSETs' ideas, and (7) making sense of responses to PSETs' ideas (Jaber et al., 2018, p. 17).

Many undergraduate laboratory experiences, including those for PSETs are shifting toward leveraging students' ideas during scientific practices (Esselman et al., 2023; Loverude et al., 2011). Given such shifts, the goal of this study is to characterize the extent to which laboratory instructors (1) attend to PSETs' curiosities and ideas and (2) work with PSETs' diverse perspectives to co-construct scientific knowledge.

As such, we adopt Mortimer's and Scott's (2003) communicative approach framework, which characterizes instructors' epistemological framing during instructor–student interactions (Russ & Luna, 2013). Instructors can take on an authoritative frame when their own ideas and questions are the focal point of instructor–student interactions. In contrast, laboratory instructors can take on the frame of a guide/facilitator when student-centered ideas are prioritized and leveraged during instructor–student interactions. In this study, we assume that when laboratory instructors prioritize and leverage student-centered ideas, they are more likely to cultivate epistemic empathy. By leveraging student-centered curiosities and ideas, laboratory instructors can scaffold PSETs' understanding of scientific phenomena through Knowledge Integration (Linn, 1995; Linn et al., 2023).

2.2 | Characterizing the repertoire of PSETs' scientific ideas

The knowledge integration (KI) framework defines science learning as a process of, "(1) adding new ideas to [a] mix of views about a topic, (2) linking and connecting new and existing ideas, (3) sorting out the ideas available, and (4) reflecting on the ideas while solving problems and restructuring views to achieve more coherence" (Linn, 1995; Linn & Hsi, 2000, p. 362; Linn et al., 2023). Phenomena-based instruction in this study provides PSETs opportunities to challenge preexisting mental models and revise models to better understand and explain phenomena. The KI framework supports the implementation of phenomena-based approaches given how it: (1) acknowledges the critical role of prior knowledge in conceptual development, (2) creates opportunities that allow PSETs to revise scientific ideas through personally meaningful investigations, and (3) aims to provide PSETs necessary scaffolding when engaging in student-led investigations.

Namdar (2018) investigated how phenomena-based instruction modeled with a KI approach supported PSETs' understanding of global climate change concepts. The results from the study indicate how phenomena-based instruction supports PSETs in developing linkages between scientific ideas to explain global climate change concepts. Namdar (2018) displays how KI approaches can support conceptual development in the context of teacher preparation courses. However, more insight is needed into why phenomena-based instruction supports some PSETs toward developing integrated connections between scientific ideas whereas others display surface-level understandings for science concepts. A potential explanation may be linked to a study that investigated how online phenomena-based instruction supported seventh-grade students' knowledge integration of evolution concepts in three different classrooms (Donnelly et al., 2016). Results indicate that KI approaches embedded within a curricular unit were able to support conceptual development pertaining to evolution. However, one instructor was able to enhance students' scientific explanations to a greater extent relative to other instructors. Concluding marks of the study suggest that knowledge integration of scientific ideas is better supported within this theory when instructors actively guide students in iterative refinement of mental models.

The KI framework is widely used throughout science education to capture nuances in students' science explanations (Lee et al., 2011; Namdar, 2018; Vitale et al., 2016). In this study, we use the KI framework to distinguish between four levels of student understanding (Donnelly et al., 2016): (1) the first level includes a fragmented understanding in which students display difficulties in making connections between scientific ideas, (2) the second level displays a basic understanding in which students can provide simple links between scientific ideas, (3) students display the third level of understanding when they can provide more elaborate links between scientific ideas, and (4) finally, students display a complex understanding when they can provide multiple links between scientific ideas. With this distinction between types of understanding, we constructed KI rubrics which allow us to capture nuanced changes in PSETs' scientific explanations.

2.3 | Characterizing instructor and student interactions during science learning

There is a general consensus that PSETs need opportunities to plan and conduct high-quality investigations to support science instruction in future K-12 classrooms (National Research Council, 2012; Özer & Sarıbaş, 2023). To date, much research has cast a deficit perspective on PSETs' ability to plan and carry out investigations (Crawford, 2007; Gray et al., 2022). For example, it has been found that due to PSETs' "insufficient level of scientific competency", they are not capable of posing questions suitable for scientific investigations (Cruz-Guzmán et al., 2017, p. 172). In a follow-up study conducted by García-Carmona et al. (2017), PSETs designed phenomena-based investigations. The study found that PSETs "expressed great difficulty in thinking ahead to the inference that they planned to make from the data" (García-Carmona et al., 2017, p. 1005). As such, the researchers note how PSETs' investigations mark a missed opportunity in terms of developing a comprehensive understanding of scientific phenomena. Furthermore, García-Carmona et al. (2018) concluded that PSETs are capable of carrying out experimental activities yet challenges emerge when developing explanatory models for why phenomena occur. Such findings highlight the need for laboratory instructors to support PSETs in designing fruitful investigations that can provide rich opportunities for knowledge construction (Agustian et al., 2022; Manz et al., 2020). As such, research should further investigate how conceptual understanding of phenomena is related to the guidance or lack thereof provided by laboratory instructors during phenomena-based investigations.

During phenomena-based instruction, a drastic shift in classroom dynamics requires laboratory instructors and PSETs to rely on one another when working through scientific uncertainties (Avery & Meyer, 2012; Jaber et al., 2018). This study uses Mortimer's and Scott's (2003) analytic framework for scientific discourse to explore how university laboratory instructors scaffold PSETs' investigations. At the heart of this framework is the communicative approach which classifies instructor–student interactions based on two dimensions. The first dimension classifies interactions as being interactive or noninteractive. Interactive discourse invites PSETs to participate in a scientific conversation, whereas noninteractive discourse represents a presentation of expert ideas. The second dimension distinguishes between authoritative and dialogic interactions. Authoritative interactions involve discourse patterns that focus on a single perspective, whereas dialogic interactions take into consideration multiple perspectives. Correspondingly, the communicative approach distinguishes between four types of instructor–student interactions: (1) authoritative–noninteractive, (2). authoritative–interactive, (3) dialogic–noninteractive, and (4) dialogic–interactive interactions (Figure 1).

Authoritative–noninteractive interactions (1) occur when instructors use traditional didactic approaches such as lecturing (Mortimer & Scott, 2003). As such, there are limited contexts in which an instructor should use authoritative–noninteractive interactions during

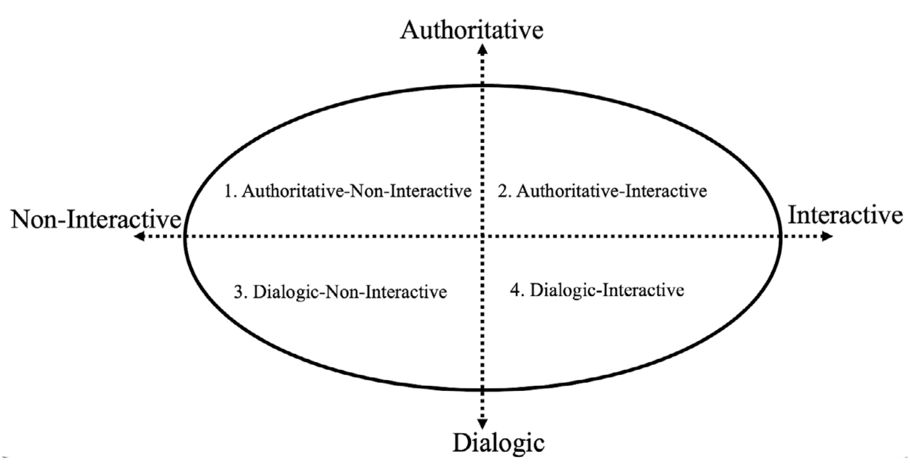

FIGURE 1 Mortimer's and Scott's (2003) communicative approach framework for characterizing instructor–student interactions. Interaction types are grouped according to two axes. The x-axis categorizes interactions into interactive or noninteractive discourse. The y-axis represents a continuum that categorizes interactions into authoritative or dialogic discourse.

phenomena-based approaches. If authoritative–noninteractive interactions are to be leveraged, one such circumstance could include presentation of demonstrations that contradict what PSETs might expect under a set of conditions (Lamnina & Chase, 2021). As such, instructors should use authority to create opportunities that motivate PSETs to seek information in the face of knowledge gaps. However, authoritative–noninteractive interactions should be limited as such discourse can restrict student-led investigations to satisfying implicit rules or ideas presented by the instructor (Berland et al., 2016).

Authoritative–interactive (2) discourse invites student contribution yet places emphasis on redirecting PSETs' thoughts to align with instructor ideas. Authoritative–interactive dialogue represents triadic initiate–respond–evaluate (IRE) sequences when PSETs answer questions in hopes that it aligns with predefined answers (Lemke, 1990). Authoritative–interactive interactions likely inhibit PSETs' motivation to engage in phenomena-based investigations as such interaction types communicate that there is only one right way to solve problems (von Glasersfeld, 1989).

A recent study demonstrated the productive use of instructor authority during phenomena-based instruction when a student displayed struggle with the following instructor-initiated question, "Why is something an insulator or conductor?" (Kim, 2022, p. 1939). Through a sequence of Initiate–Response (IR) like interactions, the student was able to recognize a knowledge gap. Upon creating cognitive conflict, the instructor facilitated a whole-class discussion in which peers' ideas about electrons, movement, and conductors were linked together and co-constructed to fill the student's knowledge gaps. This example illustrates how university laboratory instructors can effectively leverage authoritative interactions to provide opportunities that support student-centered interactions (Aguiar et al., 2010).

If dialogic–noninteractive (3.) approaches are implemented, then instructors adopt the role as a facilitator by highlighting similarities and differences in how PSETs may be thinking about a particular topic. Laboratory instructors should use dialogic–noninteractive dialogue when foregrounding opportunities to co-construct knowledge. Thus, when supported adequately, dialogic–noninteractive discourse allows students to build on each other's ideas to develop a common understanding of phenomena. Dialogic–noninteractive talk moves can foster rich opportunities for PSETs to consider contrasting scientific views and revise mental models by considering other student-driven ideas. However, Furberg and Silseth (2022) provide insight into tensions instructors experience when supporting dialogic–noninteractive discourse. For example, an instructor-initiated dialogue to gain insight into how students were thinking about gene transfer. The instructor realized how students' ideas did not align with his own. Therefore, in order to relieve tension between conceptual framings brought forward by the students, the instructor assumed an authoritative position by redirecting the student's reasoning toward his prevalidated ideas.

Dialogic–interactive (4) interactions do not provide a final evaluation of PSETs' scientific ideas. Instead, dialogic–interactive discussions value the diverse array of ideas PSETs bring to the classroom. Thus, laboratory instructors need to use a variety of questioning strategies to engage PSETs in open-chains of interactions (Chin, 2007). For example, laboratory instructors can use explication questions that ask PSETs to describe what happened during their investigations, explanation questions that ask why or how a phenomenon occurred, science concept questions that ask PSETs to use scientific language to name phenomenon, or scientific practice questions which provide PSETs an opportunity to engage in scientific practices (Benedict-Chambers et al., 2017). Aguiar et al. (2010) highlight how dialogic–interactive interactions provide rich opportunities that: (1) motivate science learning, (2) engage learners in scientific problem solving, and (3) support a safe space for learning (Aguiar et al., 2010).

If instructors support dialogic–interactive approaches, then PSETs will have greater opportunities to resolve inconsistencies in their own knowledge when confronted with alternative arguments or explanations. In the context of phenomena-based instruction, dialogic–interactive approaches are critical given how university laboratory instructors will be asked to guide PSETs through several checkpoints during investigations including but not limited to controlling variables, execution of experimental techniques, interpretation of experimental findings, and presentation of findings. Thus, dialogic–interactive approaches serve a significant purpose in legitimizing PSETs' roles as active agents in recognizing gaps in investigations and knowledge according to their own expectations (Lowell et al., 2021).

3 | METHOD

3.1 | Research design

This mixed-methods approach follows a convergent parallel design in which qualitative and quantitative data were collected together (Creswell & Plano Clark, 2017), yet analyzed independently to understand how PSETs' perceptions of their instructor's role (qualitative) influence the development of scientific explanations (quantitative) and how instructor–student interactions support perspectives on authentic science learning (qualitative). To establish trustworthiness and validity, we triangulated results to demonstrate similarities and differences in findings emerging from data sources collected within this study (Flick, 2018).

3.2 | Participants

Study participants ($n = 121$) include PSETs enrolled in a Physical Science course at a Hispanic Serving Institution (HSI) located in the western United States. Study participants within this study include underrepresented populations in Science, Technology, Engineering, and Mathematics (STEM) fields accounting for 90% female PSETs ($n = 109$) along with diverse ethnic representation including 67% Hispanic/Latinx ($n = 81$), 20% White ($n = 24$), 7% Asian ($n = 8$), 2% Black ($n = 3$), and 2% other ($n = 2$). A few PSETs ($n = 3$) declined to state their demographic information. Participation in this study was optional and PSETs were aware that their informed consent or lack thereof would have no impact on overall course grades. University-level IRB approval was obtained for this study.

The two university laboratory instructors, Jim an Asian male instructor and Mike a White male instructor (pseudonyms) have disciplinary expertise in the Physical Sciences with both possessing a Master's degree. Each instructor taught three laboratory sections, with approximately 20 PSETs in each section. Mike taught 62 PSETs, whereas Jim taught 59 PSETs.

Both instructors participated in professional development (PD) before facilitating laboratory instruction. PD was offered through an introductory presentation developed to support laboratory instructors' understanding of how to support phenomena-based instruction addressing: (1) an overview of the course, (2) discussion of the instructor manual, (3) discussion of Canvas, (4) structure of weekly meetings, and (5) discussion of the introduction laboratory activity. The introductory presentation was 2 h and new laboratory instructors had one-to-one meetings with the original developer of the laboratory curriculum. Further, laboratory instructors attended weekly 30-min meetings that prompted discussion around the following: (1) challenges related to supporting instruction in the previous week, (2) addressing the structure of the upcoming laboratory, and (3) support that was needed for both instructors and PSETs. The time assigned for PD and weekly meetings was determined by instructor union contracts.

3.3 | Course structure

Supporting meaningful learning opportunities is key to fostering student-centered science instruction. The goals of the laboratory course in this study are to engage PSETs' pre-existing conceptions as scaffolding points to help develop coherent understandings for phenomena as they, "...frame scientific questions pertinent to their interests, conduct investigations and seek out relevant scientific arguments and data, review and apply those arguments to the situation at hand, and communicate their scientific understanding and arguments to others" (National Research Council, 2012, as cited by Furtak & Penuel, 2019, p. 175).

Meaningful science instruction leverages anchor phenomenon questions to help PSETs recognize gaps in their own knowledge (Kang et al., 2014; Nordine et al., 2011). An anchoring phenomenon question reflects a puzzling event or process such as, why do objects sink or float?

The anchoring phenomenon routine is implemented at the K-12 level to provide students opportunities to co-construct meaningful questions for investigation through four key instructional components: (1) exploring anchoring phenomenon, (2) making sense of phenomena, (3) identifying related phenomena, and (4) developing questions. Research suggests that PSETs run into challenges when proposing scientific questions for experimentation (Cruz-Guzmán et al., 2017). Thus, we suggest that the anchoring phenomenon routine has utility in science-based teacher education courses, especially for helping PSETs develop fruitful investigations (Reiser et al., 2021).

As PSETs explore anchor phenomena, an instructor needs to elicit cognitive resources without providing final evaluation of ideas. Second, an instructor should support PSETs in making sense of phenomena by, "...pushing students [PSETs] to get them to realize they cannot explain something..." (Reiser et al., 2021, p. 6). For example, during an attempt to make sense of flotation, PSETs may be able to bring forth cognitive resources including but not limited to mass, volume, density, displacement, surface tension, concentration, or polarity, yet there could potentially be challenges in conceptual integration of such ideas (Andersson & Gullberg, 2014; Bell et al., 2019; Linn & Eylon, 2011; Tuysuz et al., 2016). As PSETs experience cognitive conflict, the instructor needs to provide scaffolding that helps connect phenomena to prior knowledge or experiences. Finally, the last step involves supporting PSETs in proposing investigative questions by linking cognitive conflict encountered during sensemaking to prior knowledge or experiences (Furtak & Penuel, 2019; Kang et al., 2016; Valls-Bautista et al., 2021). For the purposes of this study, a previously conducted pilot study provides insight into how the anchoring phenomenon routine is supported during student-based discussions that precede laboratory instruction (Hinde, 2019, p. 57).

The first 3 weeks of laboratory instruction engage PSETs in three bootcamp laboratory sessions providing opportunities to acquire fundamental scientific skills, essential to engage in phenomena-based investigations. The purpose of the bootcamps is to develop fundamental scientific skills such as question asking, developing testable hypotheses, collecting accurate and precise data, reporting data, and drawing evidence-based conclusions. For example, bootcamp activities during week 2, PSETs plan and conduct investigations to determine variables that influence the period of a pendulum. During the pendulum investigation, PSETs decide on specific variables to investigate, collect data, graph data, and discuss findings through instructor facilitated discussions.

Upon the completion of bootcamp laboratories, PSETs engage in 10 phenomena-based investigations throughout the semester. Prelaboratory submissions require PSETs to write a proposal on how they plan on conducting an investigation that aligns with their investigative question. Prelaboratory submissions are designed to provide PSETs ownership in developing a testable hypothesis, developing an equipment list, and conducting research on concepts, theories, and equations that can support investigations within the laboratory setting. Following investigations, post-laboratory submissions ask PSETs to make sense of the data collected during investigations by producing data tables and graphs, performing calculations, and drawing evidence-based conclusions. Table S1 provides insight into how laboratory investigations throughout the semester support PSETs to refine mental models in relation to target concepts that appear on pre- and post-assessments.

3.4 | Data sources

PSETs' questionnaire comments regarding ownership during laboratory instruction were collected at the end of the semester. PSETs' responses to questionnaire items were used to capture insight into whether instructor and student roles during instruction support or restrict the level of autonomy intended within a phenomena-based learning environment (Table S2). Additionally, laboratory instructors responded to an instructor questionnaire that sheds light on instructors' perceptions of PSETs' role during laboratory instruction. Furthermore, the instructor questionnaire provides insight into challenges associated with scaffolding PSETs' investigations (Table S3).

To measure the development of scientific explanations over the course of the semester, PSETs responded to nine conceptual items that appeared on the pre- and post-assessments. Table 1 provides the nine conceptual items as well as in which order they appear in the pre- and post-assessment. Additionally, we collected video observations that capture how instructors balance instructor-centered and student-centered dialogue during phenomena-based instruction. Video observations were conducted based on when instructors granted the first author permission to observe. Our intention was to make the instructors feel more comfortable being observed by having them choose the class for observation. Video observation of Jim's class was carried out earlier in the semester (Experiment 4) when PSETs' investigations were grounded in the following anchor phenomenon question, "Is there a difference between pressure on a surface and pressure in a container?" Video observation of Mike's classroom was not conducted until the semester came to a close (Experiment 9) when investigations were grounded in the anchor phenomenon question, "Where does light come from and go?" One video observation was conducted per instructor to capture insight into teacher–student interactions during instruction. Each video observation recorded an entire laboratory investigation averaging 1 h and 50 min each.

3.5 | Data analysis

3.5.1 | Whether and to what extent are PSETs' perceptions of their Instructor's role associated with their pre-/post-conceptual development

Mortimer's and Scott's (2003) communicative approach highlights how instructor–student interactions can vary according to two dimensions: (1) whose perspectives are valued and

TABLE 1 Pre-/post-assessment items.

Questions	Target concepts
1. On an open road on a sunny day, a driver not wearing their seatbelt slams on the brakes of their car. What immediately happens to the driver and to the car? Explain your answer.	Newton's first law, force and motion
2. Why should soap and water be used to clean animals after an oil spill rather than just water? Assume the soap is animal friendly. Explain your answer.	Entropy and intermolecular forces
3. Explain how each of these situations results in pressure: (a) A person pushing against a nail (b) Gas particles in a container	Force, area, and pressure
4. A pumpkin is dropped vertically from a sixth-floor window of a building and at the same time, a second pumpkin is thrown horizontally from the same window as the first pumpkin is dropped. Assuming no air resistance and the same mass for each pumpkin, do the pumpkins hit the ground at the same or different times? Explain your answer.	Force of gravity
5. Two liters (0.53 gallon) of a saltwater sample is left outside in an open container for a day. The next day only 1.5 L (0.40 gallon) of the saltwater sample remains due to evaporation. Has evaporation caused the salt concentration in the sample to increase, decrease, or does it stay the same? Explain your answer.	States of matter and molarity
6. What is the difference between how hot air balloons function and how helium balloons function? Explain your answer.	Density and buoyancy
7. Why do birds not get electrocuted on electric wires? Explain your answer.	Conduction, voltage, and flow of electricity
8. When a bottle of soda is opened you will hear a hiss of escaping gas (carbon dioxide) and observe bubbles that suddenly appear in solution. What causes the formation of the carbon dioxide bubbles? Explain your answer.	Pressure, solubility, and temperature
9. Explain ways in which a book sitting on a table can be considered in motion.	Force, motion, and scale

(2) interactivity during discourse. More specifically, the communicative approach provides insight into instructor framing (Carlos et al., 2023; Russ & Luna, 2013): To what extent does an instructor serve as a guide, facilitating knowledge construction opportunities? To what extent does an instructor serve as an authoritative figure in the classroom? To characterize instructor framing, we analyze PSETs' perceptions of their laboratory instructor. The first and second authors independently coded PSETs' responses to the following questions:

1. What do you see as the instructor's role in your laboratory classes?
2. What do you see as your role in your laboratory classes?

For the first question noted above, we developed two main coding categories, guide/facilitator, or authoritarian/evaluator. If responses to Question 1 could not be sorted into either category, we then reviewed responses to Question 2 for further insight to sort PSETs' perceptions into these two main categories. For example, a participant's (Participant 552,825) response to

Question 1 followed as such, "teach key words and step in when needed." Such a response was difficult to code, thus when analyzing responses to Question 2 we sought out whether or not PSETs expressed ownership over their laboratory investigations. In this example, Participant 552,825 reported, "[I was] in charge of the experiment…" As such, in this instance, the participant's perception of their instructor was interpreted as a guide/facilitator. Through this process, most student responses reflected codes of (1) guide/facilitator or (2) authoritarian/evaluator. However, a few PSETs' ($n = 13$) perceptions were coded into an emergent category of (3) safety manager. Table 2 provides insight into key terms and phrases used to parse PSETs' responses into these three categories: (1) guide/facilitator, (2) authoritarian/evaluator, and (3) safety manager. Furthermore, questionnaire responses that provide insight into what the instructors should do as opposed to what the instructor did during instruction ($n = 8$) or did not provide answers to the questionnaire ($n = 8$) were excluded from further analyses. Following this coding scheme, the first and second authors independently coded 20 PSETs' questionnaire responses to Questions 1 and 2. This initial round of coding was reviewed to determine any disagreements in coding. For example, inconsistent codes were applied to instances when PSETs recognized their instructor as a safety manager, "He is here to supervise. Mainly to make sure no one gets hurt and answer questions about lab equipment." Upon reaching consensus on how codes should be applied to PSETs' questionnaire responses, we coded the remaining responses with 95.24% interrater agreement and a Cohen's κ inter-rater reliability score of 0.90.

To illustrate how PSETs' scientific explanations develop, responses to pre- and post-assessments were scored on a scale of 1–5 reflecting the KI levels. However, very few PSETs were able to display (5) complex links ($n = 21$, 1.93%—less than 2% of responses) when providing scientific explanations. As such, we scored explanations on a scale of 1–4 to overcome limitations that arise from floor effects (Wu & Shah, 2004) with scores of 5 being rescored as 4's for our analyses. Altogether KI rubrics assess scientific understanding relative to PSETs' ability to make connections between scientific ideas to address complex phenomena (Table 3).

The development of KI rubrics took several rounds of iterative refinement by the first and second authors. The first round of development was constructed based on targeted ideas or concepts. We identified links that are required to display higher level of understanding. We then broke apart such links to develop scoring guidelines for more incomplete understandings. Through this process, we developed initial rubrics to independently score a small sample of responses ($n = 50$). We compared our scoring and revisited the rubrics for further development

TABLE 2 Key terms and codes corresponding to PSETs' perceptions of their instructor's role.

Coding assignment	Key terms/phrases
Guide/facilitator	Guides us Encourages us Provides support when needed
Authoritative/evaluator	Fixes our experiments Provides criticism Teaching us lessons
Safety manager	Monitors the classroom Watches us Walks around the classroom

TABLE 3 Sample KI rubric question: When a bottle of soda is opened you will hear a hiss of escaping gas (carbon dioxide) and observe bubbles that suddenly appear in solution and what causes the formation of the carbon dioxide bubbles? Explain your answer.

Score	KI level	Criteria	Example
1	Off task	- Answers with "I don't know" - Repeat or rephrase question - Irrelevant ideas as answer	- I do not know
2	Non-normative	- Answers that only state bubbles form because of carbonation - Answers that state that the bubbles are formed by molecules other than carbon dioxide	- Because of carbonation - They form because the soda is now exposed to the air
3	Partial idea	States that bubbles form due to *one* of the following ideas: - The release of pressure - The decrease in solubility of carbon dioxide within the soda - The increase in the temperature of the soda when opened	- By opening the bottle, the pressure is released
4	Normative idea	States that bubbles form due to *two or three* of the following ideas: - The release of pressure - The decrease in solubility of carbon dioxide within the soda - The increase in the temperature of the soda when opened	- Pressure is released causing the solubility of carbon dioxide to decrease. When solubility of carbon dioxide decreases this causes the soda to increase in temperature.

with any inconsistent scoring. The rubrics underwent iterative refinement until both authors agreed on the scoring of the initial subset of responses. Table S4 displays the range of inter-rater reliability with Cohen's κ of 0.86 to 0.92 across pretest and posttest items.

To investigate associations between instructors and codes assigned to PSETs' perceptions of their instructor, we performed a chi-square test of independence. Then, given how PSETs' perceptions of their instructor shed light on idiosyncratic learning environments, we explored the effect of PSETs' perceptions on conceptual outcomes. Using repeated measures ANOVA, we compared student outcomes with perceived instructor role as the between-subjects factor and time as within-subjects factor for PSETs' KI scores on the pretest and posttest. Further, using repeated measures ANOVA, we compared KI scores with instructor as the between-subjects factor and time as within-subjects factor. Prior to conducting these analyses, we checked the distribution of KI scores on the pre- and post-assessment to verify that data meet the assumption of normality. Results from Shapiro–Wilk tests did not indicate statistically significant differences from a normal distribution with p values of 0.14 and 0.12 for the pretest and posttest respectively. Furthermore, we investigated whether gender or ethnic background plays a role in learning gains. However, no significant differences emerged.

3.5.2 | Whether and to what extent do laboratory discursive interactions align with PSET and instructor perceptions of the instructor role?

For video observations, analysis is grounded in the communicative approach to capture insight into the instructor's role during instructor–student interactions (Mortimer & Scott, 2003).

We coded event-based interactions at the utterance level into (1) authoritative–noninteractive, (2) authoritative–interactive, (3) dialogic–noninteractive, and (4) dialogic–interactive (Lehesvuori et al., 2011; Tytler & Aranda, 2015). An utterance is defined as an interaction that takes place due to an objective in mind of either the instructor or student. As such, utterances marked instances when laboratory instructors and PSETs responded to one another over the course of investigations. The dialogue that takes place during investigations has the potential to vary between different talk patterns during a given unit of analysis. For example, as challenges emerge during investigations, laboratory instructors can use authority to gain insight into PSETs' ideas. However, upon recognizing PSETs' perspective the instructor can facilitate discussion among PSETs to develop a solution to a particular problem. Under such a circumstance, PSETs have the opportunity to share their ideas through an interactive discussion with the instructor. In this hypothetical case, the interaction would be coded as dialogic–interactive. Thus, event-based analysis places focus on whether discursive episodes are dominated by instructor-centered (authoritative) or student-centered (dialogic) ideas and to what extent is discourse interactive (interactive or noninteractive).

The first author identified event-based interactions within video transcripts. In total, video observations from Jim's classroom involved identification of 25 event-based interactions, whereas Mike's classroom included identification of 28 event-based interactions. Upon distinguishing event-based interactions, the first and second authors independently coded interactions based on the communicative approach (Mortimer & Scott, 2003). For the 53 event-based interactions, the first and second authors agreed on the codes for 46 interactions. Upon the initial review of transcripts, the first and second authors negotiated agreement between five interactions in which there was disagreement in how codes were applied. The final negotiated interrater agreement percentage was 96.22%, with a Cohen's κ inter-rater reliability score of 0.94.

Upon characterizing talk moves, we realized how video transcripts revealed idiosyncratic cases in how instructors supported PSETs' science investigations. Thus, we developed broader codes to highlight differences in the instructor–student dynamic within each classroom. Considering how Mortimer's and Scott's (2003) communicative approach characterizes which ideas are valued and how ideas are exchanged, we linked interactions to broader themes that highlight the framing PSETs take on when interacting with university laboratory instructors. Framing refers to PSETs sense of "what is it that's going on here" (Goffman, 1974, as cited by Berland & Hammer, 2012, p. 71).

3.6 | Findings

3.6.1 | Whether and to what extent are PSETs' perceptions of their Instructor's role associated with their pre-/post-conceptual development?

To provide insight into our first research question, we present results that provide insight into differences in how PSETs perceive their instructor's role during phenomena-based investigations. Specifically, we focus on how such perceptions mediate PSETs' development of scientific explanations.

3.6.2 | PSETs' perceptions of their Instructor's role

A chi-square test of independence revealed a significant association with a large effect size between instructor, Jim or Mike, and PSETs' perceptions of their instructor, guide/facilitator, or authoritarian/evaluator, $\chi^2(1) = 61.89$, $p = <0.001$, $\varphi = 0.82$. Figure 2 shows patterns in how PSETs perceive their instructor. Among PSETs enrolled in Jim's course, most (80%, $n = 37$) perceived Jim as a guide or a facilitator, whereas few (20%, $n = 9$) perceived him as an authoritarian/evaluator. Sample responses as to how PSETs perceive Jim as a guide or a facilitator include,

> "I see the instructor's role as one that encourages our curiosity and helps us make connections from our ideas to the real world."
> Student 166023, Hispanic/Latinx Female Student Taught by Jim

> "To answer any questions and to help guide us with things that we are unclear of after we did our own research."
> Student 186408, Hispanic/Latinx Female Student Taught by Jim

> "I enjoyed how he would help us if we were stuck to figure out only what we needed but would challenge us rather than give us the answer."
> Student 236120, Hispanic/Latinx Female Student Taught by Jim

In contrast, a majority of PSETs (100%, $n = 46$) perceived Mike as an authoritarian/evaluator during laboratory instruction (Figure 2). Sample responses include

> "I felt like I was on my own a lot of the time and when I did get critiqued it was not always present [pleasant] or welcomed. It wasn't the best learning environment. I was only told what was wrong and when it happened it was like the smallest details were the biggest deal. Overall, this is the only lab class I hated coming to."Student 992500, Hispanic/Latinx Female Student Taught by Mike

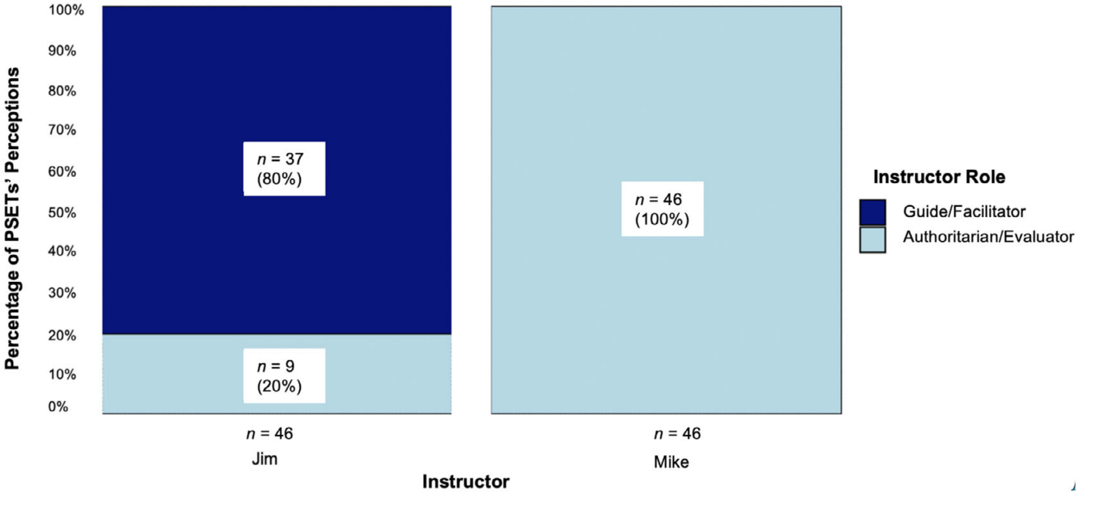

FIGURE 2 Distribution of how PSETs perceive their laboratory instructor.

"He doesn't instruct us... he walks around and won't answer our questions. Then when we show him our work he tells us everything we did wrong, even though we previously asked him for help."
Student 252604, White Female Student Taught by Mike

"He's nothing more than a babysitter. All he does is walk around and not give us any valuable input for our experiments..."
Student 091831, Hispanic/Latinx Female Student Taught by Mike

3.6.3 | Impact of instructor role on PSETs' phenomena-based explanations

A repeated measures ANOVA displays a significant interaction between time (KI gains from pretest to post-test) and how PSETs perceive their instructor ($F(1,90) = 30.36$, $p = <0.001$, $\eta^2_p = 0.25$) and a significant main effect of time ($F(1,90) = 127.27$, $p = <0.001$, $\eta^2_p = 0.59$). However, there was no main effect on PSETs' perceptions ($F(1,90) = 0.01$, $p = 0.93$, $\eta^2_p = 0.001$). PSETs who view their instructor as a guide display larger KI gains from pretest (M = 18.13, SD = 3.53, $n = 37$) to posttest (M = 24.32, SD = 3.71, $n = 37$). Interestingly, when PSETs view their instructor as an authoritative source they display smaller KI gains from pretest (M = 20.10, SD = 3.23, $n = 55$) to posttest (M = 22.23, SD = 3.78, $n = 55$). Considering how Jim was more likely to be perceived as a guide or facilitator, whereas Mike was perceived as authoritative, we examined instructor impact on PSETs' conceptual development. On average PSETs enrolled in Jim's course display larger KI gains from pretest (M = 17.98, SD = 3.61, $n = 59$) to posttest (M = 23.38, SD = 4.24, $n = 59$). Whereas, PSETs in Mike's course display smaller KI gains from pretest (M = 19.96, SD = 3.40, $n = 62$) to posttest (M = 23.16, SD = 3.68, $n = 62$). Comparison of PSETs' KI gains across laboratory instructors reveals how Jim's course displays larger KI gains despite scoring lower on the pretest relative to PSETs enrolled in Mike's course. Repeated measures analysis indicates a significant interaction effect between time and instructor, ($F(1,119) = 9.04$, $p = 0.003$, $\eta^2_p = 0.07$) with a main effect of time ($F(1,119) = 136.61$, $p = <0.001$, $\eta^2_p = 0.53$). However, there was no main effect of instructor, ($F(1,119) = 2.35$, $p = 0.128$, $\eta^2_p = 0.02$). Results indicate that PSETs' scientific explanations improve from pretest to posttest. However, PSETs that interacted with Jim display larger KI gains relative to PSETs enrolled in Mike's course (Figure 3).

3.6.4 | Whether and to what extent do laboratory discursive interactions align with PSET and instructor perceptions of the instructor role?

To provide insight into our second research question, we share how interactions align with PSETs' perceptions of their instructor's role (RQ1). We focus on how Jim and Mike facilitate instructor–student interactions during experimentation. In addition, we share instructor orientations toward supporting PSETs with phenomena-based laboratory curriculum.

Classroom observations in this study reveal differences as to how instructors shape the social environment during phenomena-based investigations. Notably, Jim primarily promotes dialogic interactions that take into consideration PSETs' scientific ideas or perspectives, whereas

Mike predominantly advances authoritative interactions that evaluate and redirect PSETs' perspectives to align with instructor expectations. As displayed in Table 4, the two prominent interaction types within Jim's course include dialogic–noninteractive and dialogic–interactive discourse. In contrast, Table 5 displays how authoritative–noninteractive and authoritative–interactive dialogue dominates interactions within Mike's course. Beyond characterizing interaction types, we highlight how differences in discursive moves influence PSETs' framing during scientific investigations. Considering how Jim enacts dialogic discourse that acknowledges PSETs' ideas, we observe that PSETs are more likely to seek out guidance during investigations and make sense of phenomena through investigations. In contrast, Mike enacts authoritative instructional approaches that critique PSETs when ideas fail to meet canonical standards. As such, we observe that PSETs avoid interactions with the instructor and realign investigations to meet expectations of the instructor.

3.7 | Instructor 1 (Jim)

Observation of Jim's classroom contained 25 event-based interactions with 15 instructor initiated-interactions and 10 student-initiated interactions. Further analysis categorized interactions as being authoritative–interactive, authoritative–noninteractive, dialogic–interactive, and dialogic–noninteractive. This analysis only accounted for conversations that centered on

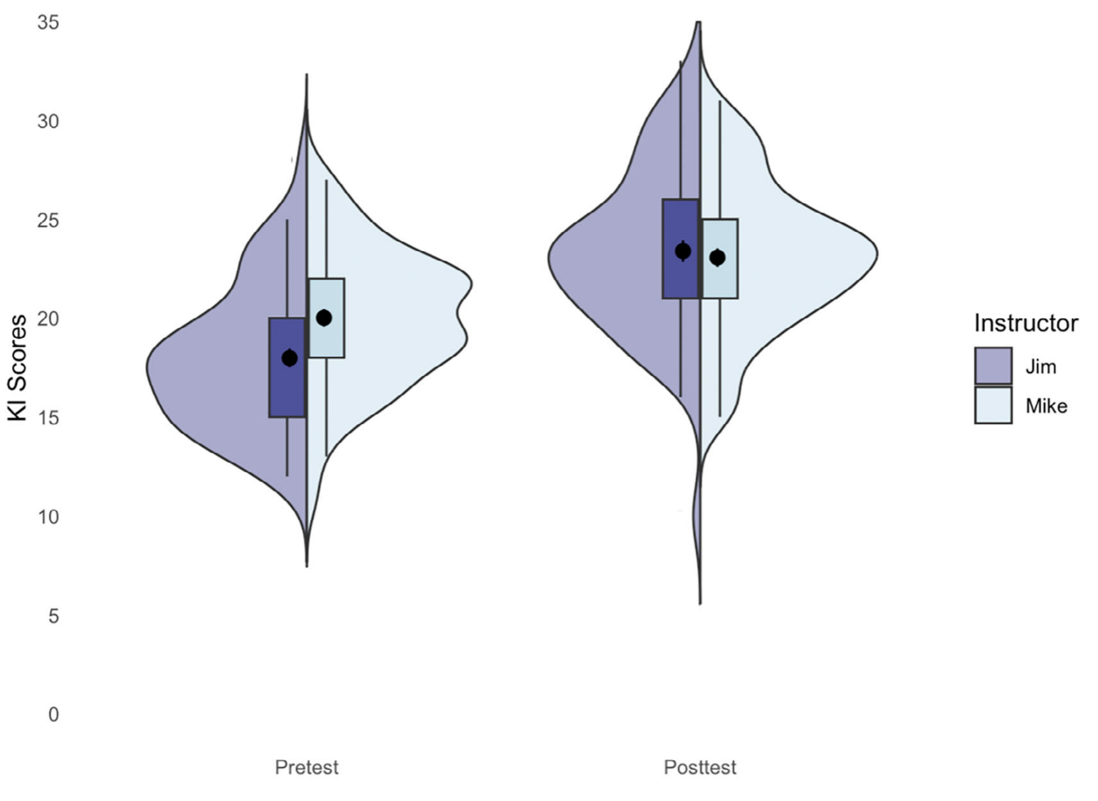

FIGURE 3 Distribution of knowledge integration scores across pre-/post-assessments disaggregated by instructor.

TABLE 4 Instructor–student interaction within Jim's classroom.

PSETs' framing with sample quotes	Categorization of prominent discourse	Sample discourse
PSETs seeking out guidance during investigations "To expand my knowledge on coming up with a hypothesis conducting an experiment, and being able to explain my reasoning on why things happened"—Student 315654	Dialogic–noninteractive	**Instructor**: Any good ideas why you think the board would rather float instead? **Student**: It has more area **Instructor**: Right, it has more area, because it has more surface area. The force over that area is much larger, right? And so that's why it is more likely to be supported per unit area. Versus the ball which is, has a lot less surface area as it just sits on top. So most likely the ball will sink up to a certain amount until it has some amount of surface area to where it will float. See. And then have you guys heard of the ideal gas laws? Nobody? Ok. Well ideal gas law is a law. How do I explain this? I'm just going to say one of the laws or phenomena that we have tested in chemistry that works on gasses. So that's why it is ideal gas laws. Not on liquids or solids. And it's given by the equation $PV = nRT$. Where pressure in atmosphere is your P. Volume in a liter is your V. n is your number of moles or the number of atoms or molecules in there. R is a gas constant for standard temperature of pressure. And then T is your temperature. And then your temperature is always done in units of Kelvin. And do you guys know what Kelvin degree temperature is?
PSETs engaged in making sense of investigations "I see my role as the one creating my own experiments and seeking to find my own answers…"—Student 244388	Dialogic–interactive	**Student**: I felt kind of confused but now we basically did pressure on the small balloon… Then our hypothesis is there will be more pressure of balloons the volume increases, so did that and it increased… So what law is this exactly? Cuz I did… **Instructor**: I don't know, I don't know what you did **Student**: Well I applied pressure towards it

TABLE 4 (Continued)

PSETs' framing with sample quotes	Categorization of prominent discourse	Sample discourse
		Instructor: Oh ok, did you apply pressure to the balloon? **Student**: Yeah, remember with the ummm, you know how we were doing it? **Instructor**: Right, I know how you were doing it. But so did you guys apply pressure to it. **Student**: Oh no it wasn't pressure then what was it... I don't know that's why I'm trying, I'm confused. **Instructor**: What did you guys do? Tell me.

scientific concepts or aspects related to PSETs' scientific investigations allowing the removal of logistical discussions ($n = 17$). Logistical discussions refer to conversational exchanges in which laboratory instructors and PSETs are not engaged in making sense of an experiment (Lippmann Kung & Linder, 2007). For example, most logistical discussions involved where to find equipment. Altogether Jim's classroom supports an environment that invites PSETs' ideas with the dominant form of interaction involving dialogic–interactive exchanges ($n = 14$; Figure 4).

Jim supports PSETs' ownership by guiding dialogic conversations around key decision-making points during phenomena-based investigations. Video observations from Jim's course reveal that when PSETs are presented with at least a few opportunities to bring forth ideas, then they are more likely to view their instructor as a guide. The use of dialogic interactions supports a learning that cultivates epistemic empathy by (1) *noticing and appreciating PSETs' emotions*, (2) *recognizing the underlying reasoning for PSETs' ideas*, (3) *finding merit in PSETs' ideas*, (4) *noticing patterns and shifts in how PSETs engage in scientific reasoning*, and (5) *expressing curiosity in PSETs' ideas* (Jaber et al., 2018, p. 17).

3.7.1 | PSETs seeking out guidance during investigations

Consistent with the literature, observations of Jim's classroom capture how PSETs can run into challenges when proposing scientific questions and experimental designs for investigations (Cruz-Guzmán et al., 2017). In this instance, when PSETs recognized that their proposed experiment was not supported by the laboratory, Jim *acknowledged their emotions* and attempted to alleviate frustration by *recognizing the underlying ideas* within their originally designed experiments and repurposing those ideas into a different experimental design. In the following interaction, PSETs experience frustration as their original experiment is not supported by the laboratory. In turn, they seek out guidance to revise their investigation:

> **Instructor**: Ok, so what was your lab? Maybe we can compromise here.
> **Female Student 1**: So we had candy and wanted to put it into soda.

TABLE 5 Instructor–student interaction within Mike's classroom.

PSETs' framing with sample quotes	Categorization of prominent discourse	Sample discourse
PSETs revising investigations to satisfy their instructor "…[I am] a student who gets criticized for making mistakes…"—Student 804819	Authoritative–noninteractive	**Student**: We're changing our hypothesis. **Instructor**: But you haven't written about it. We've altered our hypothesis from time to length. You think this was enough explanation.…And this is just tacked on the end and not a very good explanation, I'm just going to put it out there. Okay. Now you've got a chance you can write it up better now or you can just leave it like this for posterity and somebody is going to go back and say what the hell happened here. What the deuce happened here I should say.
PSETs avoiding interaction to steer clear from criticism "I felt like I was on my own a lot of the time and when I did get critiqued it was not always present [pleasant] or welcomed…"—Student 992500	Authoritative–interactive	**Instructor**: So you're trying out your optical items, are you? Cool. Were you using a laser pointer? **Student**: Yeah, blue **Instructor**: Well violet. Be careful. **Instructor**: You did the characteristic? **Student**: Yeah **Instructor**: Don't do that. **Instructor**: So what happened with concave and convex? Have you looked at those yet? **Student**: [Nods] **Instructor**: Excellent. **Instructor**: Did you do any angle tracing or anything like that? **Student**: What? **Instructor**: Well if you take a laser beam and point it at an angle, where does it end up? **Student**: Yeah **Instructor**: Then you can measure angles and stuff. Off-axis is sometimes just as interesting.

Instructor: So like pop rocks. Ok you can still do that with maybe other things that we have…
The balloon blows up with dry ice, you can see how much it blows up with baking soda and vinegar, you can do a different experiment, you can heat it up, you can do it at different temperatures, you can do different chemicals, it's really whatever you guys want to test out. Should I give you more time?
[Moment of silence]

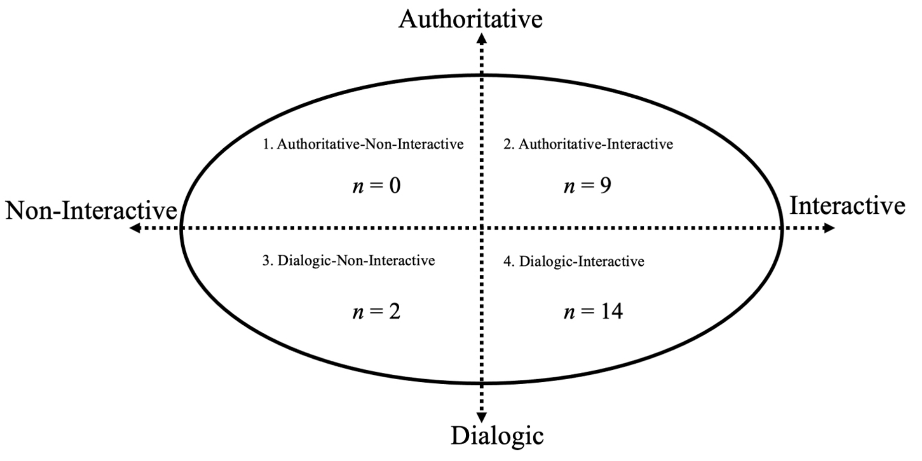

FIGURE 4 Characterization of instructor–student interactions that occur within Jim's classroom.

> **Female Student 1**: If we have any more time we are going to sit here not knowing what to do.
> **Instructor**: I want you to explore, what are you curious about? What do you know? What do you guys want to figure out?

Although Jim alleviates frustration, this particular interaction is unique in how he concludes the interaction by stating, "I want you to explore, what are you curious about? What do you know? What do you guys want to figure out?" During this interaction, Jim contextualized experiments within the scope of PSETs' underlying scientific ideas, thus he was able to engage PSETs in scientific inquiries that may not have motivated them previously (Bevins & Price, 2016; Phillips et al., 2018). During the interaction, he directs PSETs' attention toward designing predefined experiments. However, it is important to note how he withdrew from the interaction respecting PSETs' agency in designing and conducting their own investigations. This interaction highlights that although Jim attempts to support dialogic interactions, it is important to recognize that he experienced tension between supporting PSETs' ownership and guiding PSETs' brainstorming of experimental designs.

Correspondingly, many PSETs enjoy the phenomena-based instruction supported in Jim's classroom as many of them appreciate the freedom to personalize their own science investigations. However, classroom observations capture instances when Jim faces conflict in balancing guidance and PSETs' ownership during a safety concern. For example,

> **Female Student 1**: So, do we have to heat the can up with a Bunsen burner or can we use a hot plate?
> **Instructor**: Well, I'll let you decide.
> **Female Student 2**: Well, we are scared, like will it work, or will it blow up or something?
> **Instructor**: Yes, you can use an aluminum can on a hot plate.
> **Female Student 1**: Will it work the same as the Bunsen burner?
> **Female Student 3**: Which one will heat it up faster?
> **Instructor**: I don't know, I'll let you decide.
> **Female Student 2**: [Expresses slight frustration]

In the interaction above, PSETs display a lack of confidence in executing a scientific task. PSETs attempt to gain control over the unexpected by seeking information from the instructor. As such PSETs rely on the instructor to provide guidance pertaining to the use of a hot plate. However, Jim attempts to promote student agency in the classroom by encouraging PSETs to figure it out. This interaction displays the difficulty laboratory instructors face when navigating interactions within a student-centered learning environment. Although laboratory instruction creates opportunities that allow PSETs to grapple with scientific uncertainty, there are certain times when instructor guidance is needed.

3.7.2 | PSETs engaged in making sense of investigations

Jim supports a learning environment that provides opportunities to engage in scientific reasoning based on evidence collected during PSETs' investigations. In the following interaction, Jim elicits PSETs' understanding of an observed phenomenon:

> **Female Student 2**: [Excited] Look! Jim we did it!
> **Instructor**: What did we do, what?
> **Female Student 1**: [Shows instructor crushed can] We did cold water and warm water.
> **Instructor**: Awesome! What if you guys made it even hotter? What do you guys think would happen?
> **Instructor**: So why do you guys think it crushed?
> **Female Student 1**: We think it's because of the temperature difference, like we would heat up the can and with the cold water it creates some kind of suction, because with the hot water it did not do anything.
> **Instructor**: So almost nothing happened, right?
> **Students**: Yeah.
> **Instructor**: So temperature is also connected to what?
> **Female Student 1**: Pressure and volume.
> **Instructor**: So if the temperature didn't change would the pressure or volume change?
> **Female Student 1**: No.
> **Instructor**: So if the temperature did change a lot, what would happen to the volume and pressure?
> **Female Student 2**: Wouldn't it create more pressure?
> **Instructor**: So let's say we have your can and you are heating it up, but what's happening to the things that are inside?
> **Female Student 1**: I know what to say but don't know how to say it.

In the interaction above, Jim facilitates dialogic–interactive discourse to engage PSETs' scientific ideas. Further, Jim works with students to provide individualized feedback during PSETs' investigations. This active approach displayed by Jim allows PSETs to reflect on limitations of their scientific understanding and presents opportunities to co-construct conceptual understanding from evidence gathered during investigations. For example, Jim posed a follow-up question when PSETs displayed excitement about their experimental observations. During this interaction, Jim *expresses curiosity in PSETs' ideas*. Initially, PSETs display excitement when using everyday language to explain why the can is crushed during their investigation. As PSETs use everyday language to explain what emerged during their investigation, many cognitive resources are brought into the discussion. As such, Jim *finds merit in PSETs' ideas* by eliciting their conceptual understanding of the observed phenomenon during experimentation. Although Jim elicits PSETs' conceptual understanding, it appears that Jim expected an explanation aligned with scientific canon. Jim valued PSETs' ability to string together canonical scientific ideas that underlie the ideal gas law ($PV = nRT$). Given how a PSET stated, "I know what to say but don't know how to say it", there appears to be an emphasis on guiding PSETs' ideas to align with predetermined canonical answers. However, upon recognizing how PSETs were experiencing challenges in aligning their ideas to scientific canon, it appears that Jim *noticed a shift in how PSETs engaged in scientific reasoning*. Given how he withdraws from the interaction to give PSETs time to think about his question, it appears that Jim may have recognized that he was beginning to guide PSETs to a predefined answer. Differences in how Jim and PSETs approach this interaction points toward the critical role of instructors in recognizing the underlying reasoning of PSETs. Although Jim attempts to support PSETs' knowledge integration by inviting them to explain their scientific ideas, differences in what is expected during interactions cause PSETs to withdraw from this opportunity. As a result, the opportunity to further develop PSETs' mechanistic understanding is prematurely stifled.

3.7.3 | Instructor 2 (Mike)

Classroom observations of Mike's classroom display evidence of a passive classroom environment. The classroom dynamic is captured in the video observation of 28 event-based interactions with many more instructor-initiated ($n = 24$) exchanges in comparison to student-initiated exchanges ($n = 4$). All logistical discussions ($n = 28$) were removed from the analysis when classifying interactions as being authoritative–interactive, authoritative–noninteractive, dialogic–interactive, and dialogic–noninteractive. Results display how Mike pushed aside PSETs' scientific ideas with most classroom discussions being classified as authoritative–noninteractive ($n = 15$) and authoritative–interactive ($n = 13$). Altogether Mike creates an environment where PSETs fall under the impression that their ideas must align with the accepted ideas of the instructor (Figure 5).

3.7.4 | PSETs avoiding interaction to steer clear from criticism

Mike mainly initiated authoritative interactions providing PSETs little to no guidance during student-led investigations. For example, during laboratory investigations, Mike walked around the classroom asking PSETs, "How are you doing?" An interesting observation captures how PSETs rarely initiate interactions with Mike. During experimental challenges, PSETs refrained from asking for guidance. If PSETs experienced challenges during investigations, Mike provided little to no guidance as seen in the following interaction:

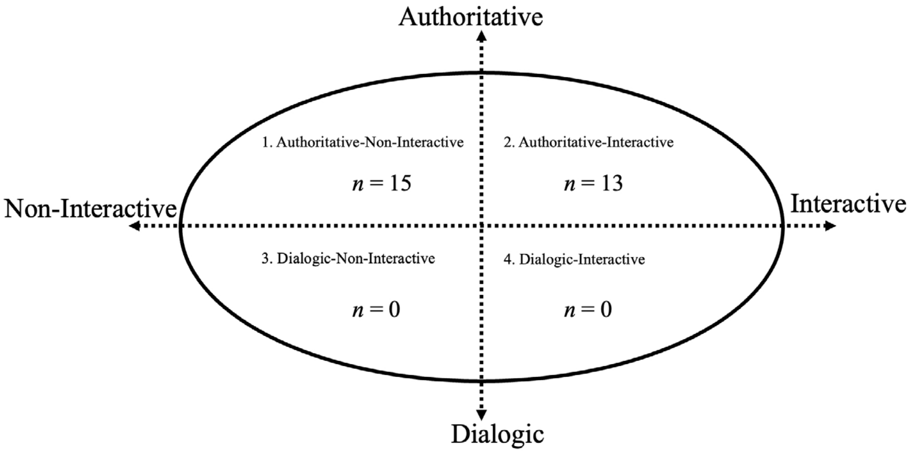

FIGURE 5 Characterization of instructor–student interactions that occur within Mike's classroom.

> **Instructor**: What are we trying to do?
> **Male Student**: Oh we're just making some observations of how light refracts in water.
> **Instructor**: Oh.
> **Male Student**: It's pretty cool, I was looking at it too, but I didn't really understand it, so they can explain it.
> **Instructor**: Cool, yes, the light is refracted and turns into a mirror image. It's cool, very cool. [Walks away]

As shown above, the interactivity of exchanges between instructor and PSETs is kept to a minimum. The PSET creates an interactional rupture in which he states a lack of understanding for his own investigation. An interactional rupture refers to an unexpected break during an interaction (Beghetto, 2016). During this instance, the interactional rupture presents a tremendous opportunity in which the instructor can engage prior ideas to facilitate understanding, yet Mike does not leverage the opportunity leaving the confusion unaddressed. Thus, it should be no surprise that PSETs taught by Mike experience a lack of support. Overall, classroom observations reveal how Mike leaves PSETs' confusions unaddressed. As such, Mike fails to cultivate epistemic empathy as he makes no attempt to *recognize the underlying reasoning for PSETs' ideas*, *find merit in PSETs' ideas*, and *express curiosity in PSETs' ideas*.

3.7.5 | PSETs revising investigations to satisfy their instructor

Due to Mike's passive role as an instructor, PSETs display a lack of engagement as they carry out scientific investigations. Instructor passivity refers to when instructors are not actively supporting PSETs in connecting experimental activities to phenomena, explaining scientific concepts, or producing experimental evidence (Asay & Orgill, 2010).

It was only toward the end of instruction, when PSETs initiated dialogue in hopes that their scientific work satisfied conditions needed for Mike's signature. As instruction came to a close, Mike critiqued investigations and provided PSETs with a list of corrections needed in order to obtain a signature. Due to minimal instructor–student negotiation during investigations, PSETs in Mike's classroom lack access to task structuring and hints that are essential for learning in phenomena-based learning environments (Chen, 2022; Chen & Qiao, 2020; Hmelo-Silver et al., 2007).

In turn features of scientific practices such as analyzing and interpreting data, constructing explanations and designing solutions, and obtaining, evaluating, and communicating information became absent in the classroom. Therefore, given his passive role during PSETs' investigations, he was unable to *notice patterns and shifts in how PSETs engage in scientific reasoning*. Further, Mike's instructional approach evaluates PSETs on their experimental designs, and provides little to no support in building an understanding of phenomena captured within investigations (Manz et al., 2020). Thus, minimal guidance along with a focus on evaluating experimental designs explains why PSETs perceive Mike as an authoritative figure. As such, Mike's instructional approaches suppress the opportunity to create a learning environment that nurtures meaningful science investigations. Instead, PSETs shift their focus toward satisfying Mike's expectations and obtaining a signature in order to leave the classroom. As such, there was an increased level of interaction when instruction came to an end. The following interaction displays how the instructor creates a classroom environment that minimizes PSETs' agency in the classroom:

> **Female Student 1**: We're done.
> **Instructor**: Ok, there is nothing else you can do with your glow sticks? Because there's time, you've got 50 minutes if you want to try some other experimentation. You could maybe do the refraction of light through water of different temperatures?
> **Female Student 1**: Well, I don't think we can get it any colder than it already is, we don't have ice.
> **Instructor**: Well you can use hot water…
> **Female Student 1**: Well like that's what we did… [Further explains]
> **Instructor**: Ok, Ok [Goes on with reading students' laboratory notes]
> **Instructor**: Your hypothesis was talking about rates. And when we talk about rates. We get out a stopwatch and measure, don't we?
> **Female Student 1**: Umm-hmmm.
> **Instructor**: Quickly go do that. You got plenty of time.
> **Female Student 1**: …But we can always change the hypothesis rather than change all our data, because we already wrote our results.
> **Instructor**: Well you can talk about that now, you can talk about how you are changing your hypothesis now.
> **Instructor**: Just write further notes on what you're doing now… That's what you can do now. And then I'll sign off on it…

It is important to note that most of the interactions that occurred within the classroom observation took place during this evaluation period when the instructor checks PSETs' work. Thus, interactions center on the instructor identifying flaws within PSETs' investigations. Although Mike allows PSETs to conduct their investigations with little guidance, his passive role in problematizing and sensemaking create a product-oriented environment. Furthermore, the authoritative position Mike assumes causes many PSETs to develop an aversion to science practices. In the following interaction, PSETs show resistance toward engaging in further experimentation:

Female Student: Hi, can you check this?
Instructor: I can look at it, yeah, you're not going to try anything else with your experiment?
Female Student: No. [inaudible]
Instructor: Did you try looking at the light through a prism?
Female Student: [Nods]
Instructor: Ok, you're obviously busy. [Looks over work and provides signature]

3.7.6 | Instructor orientations

Despite implementing instructional strategies that supported positive science experiences, Jim expresses a deficit view toward PSETs' ability to engage in science practices:

> "I really like this style of exploration based learning, however I don't think this style is for students who don't even understand the basics of the basics....The main challenge is how linear their level of thinking has become. They understand that they can change variables and test them to see an outcome, however they lack the basic fundamentals of why those things happen....Their lack of understanding is not their fault, it isn't in them to connect the dots…"

As can be seen, Jim takes a stance that PSETs have not received enough conceptual or theoretical information to seek out answers to questions about everyday phenomena. Such views are problematic as it communicates, authentic science work is for the elite who have developed scientific expertise.

When asking Mike about his instructional approach he emphasizes involvement prior to experimentation and after experimentation, confirming a role that provides little to no support in facilitating knowledge integration during investigations:

> "I was involved in looking over experiments before submission. I helped provide pre-experiment presentations directed at providing information for successful completion of experiments and hopefully filling in a few knowledge holes."

Both orientations toward supporting authentic science practices provide insight into potential barriers university laboratory instructors face when supporting learning environments for science courses meant for teacher preparation programs.

4 | DISCUSSION

This study builds on prior research that characterizes how students perceive their instructor within phenomena-based laboratory curricula (Kendall & Schussler, 2012; Ovid et al., 2021) and investigates the dynamic of instructor–student interactions during phenomena-based investigations (Chen & Techawitthayachinda, 2021; Donnelly et al., 2014). This study provides insight into the relationship between perceptions regarding an instructor's role and student learning outcomes (RQ1) along with the importance of instructor–student interactions in cultivating a student-centered environment (RQ2).

4.1 | Whether and to what extent are PSETs′ perceptions of their instructor′s role associated with their pre-/post-conceptual development

In this study, one of the main findings is that PSETs' perceptions of instructor role affect PSETs' development of scientific explanations. PSETs taught by Jim perceived him to be a guide/facilitator, whereas those instructed by Mike viewed him as authoritarian/evaluator. In turn, PSETs guided by Jim displayed greater KI gains relative to those who were instructed by Mike.

Prior research finds that students who perceive their instructor as being supportive also believe that they develop a stronger conceptual understanding (Wheeler et al., 2017a). Further, prior research suggests that minimal to no guidance during student-centered investigations likely stifles students' opportunities for conceptual development (Donnelly et al., 2016; Namdar, 2018). However, to our knowledge, this study is one of the first to directly investigate both perceptions of instructor role and associated pre-/post-conceptual gains, particularly within a phenomena-based laboratory structure.

A critical first step of the constructivist KI instructional framework is to elicit student ideas so that instructors can then effectively guide students to add new ideas, distinguish between existing and new ideas, and to reflect on ideas to develop a stronger conceptual understanding. As evidenced in this study, when students perceive an instructor as overtly critical of their ideas in an authoritative way, students view the science laboratory as a chore to be "done" rather than an enjoyable place to inquire and learn. However, as also evidenced in this study, when students perceive an instructor more as a facilitator ready to reason with their ideas, the science laboratory can become a place to better understand phenomena of interest. Our findings illustrate the importance for instructors to elicit and reason with student ideas in respectful ways in order to better support students' knowledge integration (Linn et al., 2023).

4.2 | Whether and to what extent do laboratory discursive interactions align with PSET and instructor perceptions of the instructor role

The findings in this study indicate differences in how laboratory instructors support instructor–student interactions, hence influencing how PSETs perceive their instructor. Shifts toward implementing phenomena-based laboratory approaches are marked by "a change in the instructor's role, from deliverer of information to facilitator" (Krystyniak & Heikkinen, 2007, p. 1181) and in how "students take responsibility for their learning" (Quattrucci, 2018, p. 259). The findings of this study align with prior research indicating how laboratory instructors can experience challenges in adopting new roles to support phenomena-based instruction (Goodwin et al., 2023; Smith et al., 2023).

In particular, Mike adopts an epistemological frame that engages PSETs in the *classroom game* (Lemke, 1990). As such, instructor–student interactions followed sequences that evaluated PSETs' ideas according to their alignment with Mike's ideas. Research conducted by Gormally et al. (2016) suggests that Mike may have lacked skills needed to facilitate student-centered interactions, but a more plausible explanation implies that Mike was reluctant in sharing authority among PSETs. Despite weekly laboratory meetings emphasizing the student-centered nature of the course, observations from Mike's classroom indicate no attempt in taking PSETs' ideas seriously. Therefore, Mike's instructional approaches convey a lack of respect for PSETs' scientific ideas, denying them the opportunity to see themselves as contributors within a student-centered learning environment. That is, an instructor who predominantly employs authoritative approaches may potentially support science learning if they can still respect students' ideas and reasoning, even if normatively incomplete or incorrect. However, Mike cultivated an instructor–student division that caused PSETs to view their investigations as scientific products that were under evaluation. These observations align with prior secondary school research indicating that when instructors use authoritative interactions to emphasize the right way to do science, it creates a power dynamic that shifts student focus from understanding scientific phenomena to meeting the instructor's expectations (Donnelly et al., 2014).

In contrast, Jim facilitates dialogic interactions (Mortimer & Scott, 2003) that support PSETs' curiosities, elicit prior knowledge, and seek out how PSETs understand phenomena. Thus, implementation of dialogic moves cultivates a learning environment in which PSETs can share authority with a practicing scientist. Although Jim supports discourse that centers PSETs' scientific ideas, both instructors face challenges co-constructing PSETs' science explanations. Notably, when Jim is trying to guide PSETs toward making sense of why a can crushes when submerged in cold water, he directs PSETs to variables that underlie the ideal gas law. This study demonstrates how practicing scientists such as Jim guide PSETs to canonical targets, despite there being a rich opportunity to co-construct a mechanistic understanding of the phenomenon of interest. Although taking place in a teacher preparation context, these findings resonate with observations at the K-12 level (Russ et al., 2009). Thus, it should be clear that there is room for improvement in how both instructors support PSETs' investigations.

Prior research displays how differences in epistemological framing influence how students engage in phenomena-based learning opportunities (Hutchison & Hammer, 2010). Considering how Jim supports student-centered interactions, it is reasonable to infer a connection between implementing dialogic interactions and the perception of an instructor as a guide/facilitator. This finding is consistent with research conducted by Goodwin et al. (2023) which reveals that students are more likely to take responsibility for their own learning when they perceive their instructor as being supportive. Further, when instructors are perceived as providing higher amounts of guidance, students are more likely to experience less anxiety in student-centered learning environments (Schussler et al., 2021). However, if students perceive their instructor as being unsupportive, they are less likely to display ownership and more likely to develop anxiety (Goodwin et al., 2023; Schussler et al., 2021). Thus, divisions in how students perceive instructors implementing the same laboratory curriculum raises concerns regarding whether undergraduate students have equal learning opportunities (Goodwin et al., 2021; Talanquer & Pollard, 2017).

4.3 | Implications for instruction

Despite some encouraging outcomes associated with Jim's instructional approach, his broader disposition of PSETs' inability to engage in investigations is problematic "Their lack of understanding is not their fault, it isn't in them to connect the dots…" Such views highlight issues regarding how some university laboratory instructors view PSETs' science preparation as being unworthy of their time. If fostering sensemaking in authentic social contexts is a goal of science education reform efforts, we need to develop a better understanding of how future teacher candidates and scientists can work together in mutualistic relationships. A lack of understanding and value in elementary teachers' role in enhancing science experiences remains an ongoing challenge within the STEM community. Science courses for future teachers need to provide inclusive and welcoming spaces, valuing all student voices, and need to recognize the critical role PSETs can and should play in the advancement of STEM disciplines.

Schafer et al. (2023) note how underlying epistemological commitments of curricula give students little to no agency in developing scientific explanations productive for figuring out how and why phenomena occur. Due in part to such epistemological commitments, this study displays tensions in creating student-centered learning opportunities by laboratory instructors. As such, future research could alleviate such tensions by focusing on teacher–scientist partnerships that help laboratory instructors develop epistemic empathy (Jaber et al., 2022), while also creating mutualistic relationships that cultivate respect for the experiences of both future teachers and scientists (Atias et al., 2023; Shanahan & Bechtel, 2020). Teacher–scientist partnerships can be cultivated such that future teacher candidates can develop insight into the challenges scientists face when generating and building upon ideas when trying to make sense of phenomena. Further, teacher–scientist partnerships can cultivate opportunities in which PSETs' pedagogical expertise is leveraged when designing an NGSS-aligned curriculum. The implementation of teacher–scientist partnerships also implies that laboratory instructors have opportunities to review exemplar communication strategies that cultivate respect for PSETs' scientific expertise. Ultimately, investigating ways to address the power imbalance between scientists and teachers can help researchers develop programs that allow teachers and scientists to focus on a shared goal of improving science education and science.

5 | CONCLUSION

Engaging PSETs in phenomena-based learning environments aligned with the NGSS can be a promising approach to support teaching practices in future K-12 classrooms. This study provides insight into the challenges science content courses at comprehensive universities face when supporting PSETs' authentic science experiences. An instructor who elicits and respects student ideas, provides opportunities to revise ideas, and co-constructs explanations will create a learning environment where PSETs perceive their instructor as guide or facilitator. In such a learning environment, PSETs are supported in building connections to their prior knowledge and as a result will develop understanding of scientific phenomena. In contrast, an instructor will be perceived as authoritative if PSETs' ideas are undervalued or evaluated solely based on alignment with scientific canon. PSETs who view their instructor as authoritative will build less connections to their prior knowledge, given the focus on satisfying the instructor.

Most studies that investigate classroom discussion occur at the K-12 level, whereas this study compares the dialogic patterns supported by two university laboratory instructors. The evidence in this study provides insight into how the classroom environment can influence PSETs' perceptions of their instructor. In addition, PSETs' perceptions of their instructor mediate the development of scientific explanations. The combination of these findings provide insight into how university laboratory instructors can shape PSETs' experiences and learning in a laboratory class. Thus, scientists who teach labs need to recognize the valuable opportunities they have for supporting enhanced instruction at the K-12 level. Further, scientists need to diversify their perceptions of the value of welcoming everyone in science and the value of each student's investigation. Despite whether scientists find student inquiries as being trivial or not, scientists need to recognize what may be trivial to an expert may not be trivial for a student. Therefore, it is essential for science departments to challenge prevailing norms in scientist–future teacher relationships, particularly on the scientist side.

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SUPPORTING INFORMATION

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

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