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Why do teachers vary in their instructional change during science PD? The role of noticing students in an iterative change process

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Abstract

Instructional shifts required by equitable, reform-based science instruction are challenging, especially in the elementary context. Such shifts require professional development (PD) that supports teacher internalization of new pedagogical strategies as well as changes in beliefs about how students learn. Because of this complexity, many PD programs struggle to foster lasting pedagogical shifts, necessitating further investigation into why some teachers successfully embrace reform practices while others do not. This qualitative study uses a nonlinear, iterative model of teacher learning (Interconnected Model of Professional Growth; Clarke & Hollingsworth, 2002) alongside professional noticing to help understand why elementary teachers in science PD differentially make sense of and internalize new pedagogies. Findings indicate that teachers most likely to adopt reform-based instructional practices from the PD were those who clearly connected student learning to their instructional moves. In addition, teachers who more actively attended to student sensemaking and productive struggle took up pedagogies from the PD more substantively than did colleagues who attended solely to student engagement and affect. Finally, teachers who attended to and valued novel ideas from students' lived experiences were more likely to change their beliefs about students' capacity to learn science, and thus more likely to see the

value of instructional practices from the PD. In sum, structuring PD to build on these specific teacher noticing skills can encourage more teachers to move away from traditional, teacher-directed instructional practice, and more fully support reform-based instructional practices.

KEYWORDS

3-dimensional instruction, equitable sensemaking discourse, internalization, lived experience, professional development, science education, teacher change, teacher noticing

1 | INTRODUCTION

The implementation of three-dimensional science instruction envisioned in the Next Generation Science Standards (NGSS Lead States, 2013) poses unique instructional challenges (Furtak, 2017; Heredia, 2020; National Research Council, 2012). It demands that core disciplinary concepts be taught alongside science practices and the crosscutting concepts that frame all science disciplines (Davis & Smithey, 2009; Luna & Sherin, 2017; Windschitl et al., 2012). In addition, supporting students' epistemic agency in an equitable manner requires that teachers draw on students' lived experience and build on their science ideas to drive curriculum, rather than center textbook canon and vocabulary (Furtak, 2017; Sandholtz & Ringstaff, 2014; Stroupe, 2014). We refer to this complex set of pedagogical approaches as reform-based instructional practices, hereinafter described as "reform practices," for brevity and clarity. The instructional challenges associated with reform practices are especially pronounced in elementary environments where teachers often feel unprepared, and where science instruction is underdeveloped, de-emphasized, and in many cases, not taught (Banilower et al., 2018; Davis & Palincsar, 2023; Dorph et al., 2011; Roth, et al., 2011; Sandholtz & Ringstaff, 2014; van Zee et al., 2005; Windschitl & Stroupe, 2017).

Over the last decade researchers have struggled with how best to support teachers' learning about the shifts required to address reformed standards. Because such instruction is so complicated, there is a need for teacher learning opportunities that address shifts at multiple levels, including not only teachers' personal beliefs and knowledge, but also the unique contexts and needs of students they are serving (Furtak, 2017; Korthagen, 2016; Manz & Suárez, 2018; van Driel et al., 2012). Perhaps unsurprisingly, many professional development efforts fail to support intended changes in teachers' instruction, that is, that reform practices become internalized in the teacher's belief system (Dolfin et al., 2021; Evans, 2014; Guskey, 2002; Sandholtz et al., 2019). Even for PD that demonstrates positive instructional outcomes, there is a need for more research on why and how some teachers take up reform practices while others seem unable to align practice and beliefs with the demands of instructional reforms (Molle, 2021; Stolk et al., 2010).

In this study we address the need to understand why teachers in science education PD differentially internalize and implement new practices following participation in PD (Arievitch & Haenen, 2005; Justi & van Driel, 2006; Robertson et al., 2016; Roth et al., 2011; Tekkumru-Kisa et al., 2017; Wilson, 2013). We present a qualitative study that explores why some teachers take up and implement reform practices more than others. Part of a larger, multiyear, NSF-funded project, this study examines the process of instructional change for 21 elementary teachers after approximately 1 year of comprehensive PD. Using an iterative model of professional growth (Clarke & Hollingsworth, 2002; Hayes et al., 2019; Justi & van Driel, 2006), we first explore what features of the professional learning process figure prominently in teachers' descriptions of their instructional change, then focus on one salient feature of instructional change – how teachers notice, attend to, and respond to student learning.

2 | TEACHER LEARNING IN PD STUDIES - RELEVANT LITERATURE

2.1 | Moving from linear to iterative in explaining variance in teacher learning

An extensive body of professional development literature has provided insight about the characteristics of high-quality PD. Early work by Desimone, Garet, and others demonstrated that effective PD is content focused; requires participants to engage in the activities experienced by students; is coherent with school contexts; is of sustained duration; and includes collective participation (Desimone, 2009; Garet et al., 2001; Wei et al., 2009). Effective PD also provides teachers opportunities to collaborate with content experts (Darling-Hammond & Richardson, 2009; Loucks-Horsley et al., 2010); and it treats content and pedagogy as intertwined, and organized around a theory of teacher learning (Kennedy, 2016; Roth et al., 2011). Research from the late 1990s and early 2000s usually conceptualized teacher learning as a linear process by which participation in PD leads to changes in teacher knowledge and beliefs, which then leads to changes in practice, resulting in improvements in student learning (Desimone, 2009; Garet et al., 2001; Guskey, 2002).

A number of science education PD studies initially used linear models to frame teacher change (Dolfing et al., 2021; Edelson et al., 2021; Finkelstein et al., 2019; Knight-Bardsley & McNeill, 2016; Maeng et al., 2020). Yet, many of the same studies found that when teachers engage in the active learning practices within PD, they experience multi-, rather than uni-directional interactions between PD, teacher knowledge and beliefs, practice, student outcomes, and organizational contexts (Wayne et al., 2008). In other words, even when PD leaders envision a linear PD design, the learning that results is often iterative and recursive, rather than linear. For example, Knight-Bardsley and McNeill (2016) designed their PD for argumentation on a unidirectional model, but found that teachers consistently reflected on their classroom experiences with facilitators in subsequent PD sessions, and reported the most learning from iterative cycles of implementation, reflection, and discussion. In addition, adherence to a linear pathway in PD design hasn't guaranteed successful uptake of expected reforms (Penuel et al., 2009). Even though they incorporated Desimone's (2009) core features of effective PD into their project, Dolfing et al. (2021) found that science teachers had difficulty making sense of content when the PD was delivered through a linear pathway. That is, when teachers had few opportunities to reflect on their learning and modify the PD design to align with their classroom contexts, teachers distanced themselves from, rather than embraced, the new practices. Opfer and Pedder (2011) and Evans (2014) were emphatic in their assessment of linear models: no matter the order (or duration), teacher learning is a complex system, not a rigid sequence of events.

To understand why teachers vary in their uptake and implementation of instructional reform during PD, we thus frame this study using a nonlinear model of teacher change that allows for iterative interactions between domains of teacher learning. We draw from the Interconnected Model of Professional Growth (Clarke & Hollingsworth, 2002). Justi and van Driel (2006) renamed it the Interconnected Model of Teacher Professional Growth. Hereinafter, for ease, we use Enderle et al.'s (2022) acronym "IMTPG."

This model comprises four domains (p. 951): (1) the **personal domain**, consisting of teacher knowledge, including content (CK) and pedagogical content knowledge (PCK; Gess-Newsome, 2015; Shulman, 1986), teacher beliefs, affect, and personal characteristics; (2) the **practice domain**, comprised of the teacher's enactments and reflections during planning and teaching; (3) the **domain of consequence**, representing teacher observation of students, including their engagement, affect, and learning; and (4) the **external domain**, which combines influences outside the teacher's personal world, such as standards, policy, organizational conditions, and the PD itself. Because our study is concerned primarily with influences of, and instructional shifts following the PD, we refer to this particular aspect of the external domain as the **activity domain** to delineate professional learning activities from other aspects of organizational influence. Interactions can move iteratively among the quadrangle of domains. For example: (a) teachers are exposed to new ideas in PD or other sources (activity domain); (b) they then try out those strategies in their classrooms (practice domain); (c) they observe how students respond to the new approaches (domain of consequence); (d) as teachers notice improvements in students' sensemaking and learning, they internalize new

PCK, and, ultimately change their beliefs about teaching and learning (personal domain) (Schipper et al., 2017) (Figure 1). Changes in one domain lead to changes in others (Clarke & Hollingsworth, 2002, p. 958; Enderle et al., 2022, p. 2022), through an iterative process of enactment and reflection (Schipper et al., 2017).

Research using such complex, iterative models across subject areas has variously demonstrated the importance of PD (activity domain in the adapted model) in teacher change, and the role of teacher personal traits (personal domain) in attending to and interpreting what they learn in PD (Goldsmith et al., 2014; Widjaja et al., 2017; Witterholt et al., 2012). Research also showcases how trying out new pedagogical strategies (practice domain) and observing student response (domain of consequence) can drive teacher adoption of, or resistance to, reform practices (Wilson, 2013; Wongsopawiro et al., 2017).

A few studies of science PD have also attended to these domains, although not always together (Enderle et al., 2022; Fernandez et al., 2023; Justi & van Driel, 2006; Southerland et al., 2023; Zwart et al., 2007). These studies provide insight into how and why some teachers in science PD internalize reform practices, while others have a more difficult time doing so. For example, Enderle et al., (2022) found that teacher beliefs (personal domain) could limit what teachers were able to take up from the PD (categorized within the external domain in their study). However, as teachers engaged in revisions of curriculum (activity domain), tried out the curriculum (practice domain), and observed student discourse (domain of consequence), they were able to shift their instructional practices. Similarly, Schipper et al. (2017) determined that teachers changed to a greater degree when they had time and freedom to experiment with new instructional practices (practice domain, activity domain) because they saw immediate results with their own students (domain of consequence).

These studies begin to explicate the complex process of teacher learning in science PD. However, most studies using complex frameworks such as the IMTPG focus on one to three case study teachers. To extend this literature, we focus on a sample of 21 teachers after the first academic year of a multiyear PD project. To understand how these teachers varied in their learning, our first research question (RQ1) attends to differentiation in teacher change

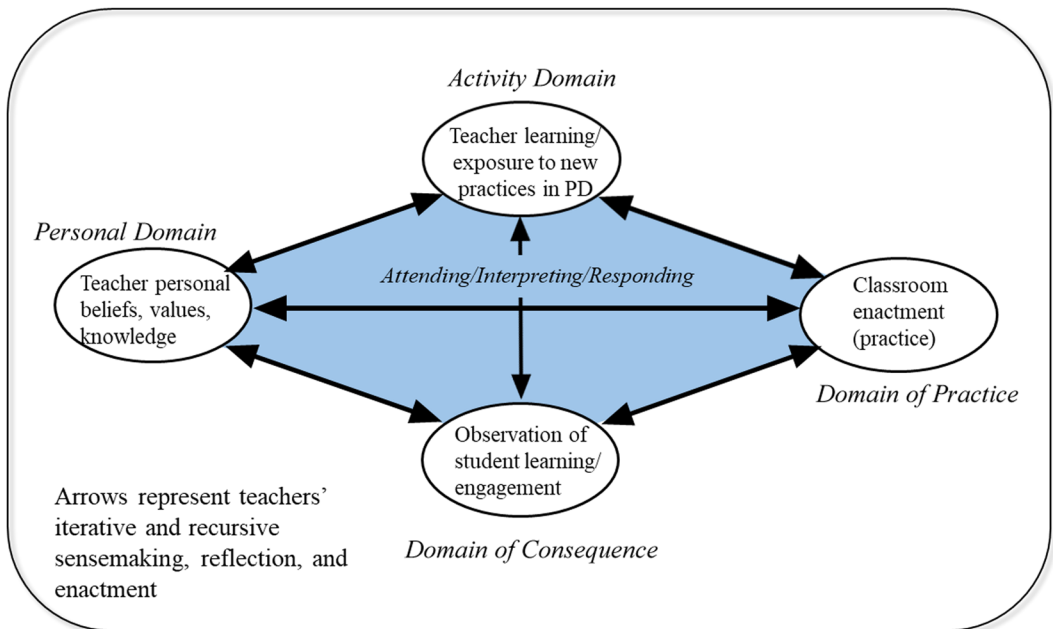


FIGURE 1 Interconnected model of professional growth, centering interactions among PD, personal beliefs, classroom practice, and student learning (Clarke & Hollingsworth, 2002), and aspects of professional noticing (Franke et al., 2001; Sherin, 2002).

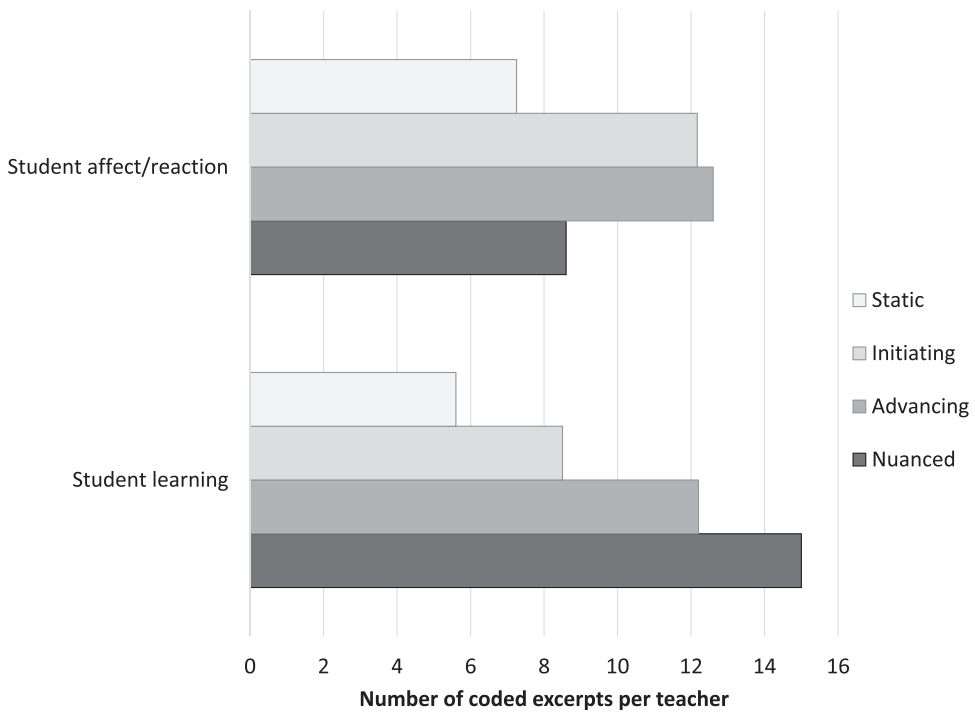


FIGURE 2 Number of interview excerpts for domain of consequence subcodes by teacher change category.

(Grossman et al., 1999). Then, to document the centrality of interactions among domains, our second research question (RQ2) uses mixed data analysis to understand the role played by each domain on teachers' instructional change.

2.2 | The role of noticing student learning in teacher change

Across many studies using the IMTPG to explain the mechanisms of professional learning, teacher attention to student learning and engagement (domain of consequence) (Clarke & Hollingsworth, 2002) has garnered particular attention (Hayes et al., 2019; Heller et al., 2012; Justi & van Driel, 2006; Lomas, 2018; Nielsen, 2012; Voogt et al., 2011). For example, both Widjaja et al. (2017) and Witterholt et al. (2012) show that, in response to trying out new strategies (practice domain, activity domain), teachers internalized such practices (personal domain) when they observed improvements in students' problem-solving (domain of consequence). In turn, acknowledgment of students' learning resulted in changes in the teacher's knowledge, beliefs, and attitudes (personal domain).

When we, too, found the domain of consequence to be central to teacher change in RQ2, we turned to the literature on professional noticing (Erickson, 2011; Jacobs et al., 2010; Sherin et al., 2011) to unpack the quadrangle of interactions (see Figure 1) between domains (Clarke & Hollingsworth, 2002; Hayes et al., 2019), and to understand how differential perceptions of student learning influence variations in the uptake of reform practices. Professional noticing consists of teachers attending to student ideas, interpreting what students are saying, making connections with content, pedagogy, and learning (van Es & Sherin, 2021); and responding with pedagogical actions (Jacobs et al., 2010).

Several studies note how degrees of sophistication in the use of noticing skills contribute to differential uptake of reform practices, and suggest that noticing skills may play an important role in teacher change (Barnhart & van



Es, 2015; Jacobs et al., 2010; Luna & Selmer, 2021; Sherin, 2002). For example, Franke et al.'s (2001) study of differential uptake of reform practices among 22 teachers in one school district found that teachers who engaged in their own sensemaking around students' learning processes—characteristics they described as “generative change (p. 653)”—were more likely to integrate students' learning strategies into instructional practice than teachers not attending as closely to student learning.

Yet, teaching practices are not always generalizable across subject areas (Alonzo & Elby, 2014; Chen et al., 2019; Kang & Anderson, 2015; Schipper et al., 2017), or even across all science topics. The complexities of reform practices require teachers to notice children's thinking in both discipline-specific (Suárez, 2020) and topic-specific ways (Gess-Newsome, 2015). When teachers attend to, interpret, and respond to students' contributions that represent substantive, emergent ideas in a fundamental science concept, they understand better how students are learning, and they are building their PCK, that is, “...the ways of representing and formulating the subject that make it comprehensible to others (Shulman, 1986).” Noticing helps shift practice away from a traditional view of the teacher as the “sole instructional, knowledge, and practice authority” (Stroupe, 2014, p. 488), and toward more student-centered inquiry, where the science ideas students bring to the classroom are built upon through exploration, critical thinking (Manz, 2012), and discourse (Bae et al., 2021; Davis & Smithey, 2009; NGSS Lead States, 2013; Sandholtz & Ringstaff, 2014; Windschitl et al., 2012).

Moreover, the noticing and positioning of emergent student ideas, speech, and language repertoires as assets for classroom learning further enhance teachers' ability to see the results of trying out new strategies from PD, integrate them with what students are thinking and saying, and ultimately internalize new pedagogies as part of their regular teaching knowledge and practice (Colley & Windschitl, 2016; Lee et al., 2019). Conversely, when teachers focus on science facts, or harbor beliefs of students as vessels to be filled, they have difficulty drawing students into a sensemaking process, and thus difficulty seeing student learning (Eastwell, 2002; Yager, 2000). Colley and Windschitl (2016) remind us that, “students' science ideas are leverageable intellectual resources that can be used by educators to support reasoning and, in turn, learning (p. 1012).” In their study, rather than teachers evaluating and amplifying only canonically correct answers, teachers engaged in responsive practice, attending to the broad spectrum of students' ideas and lived experiences, and making them public for the benefit of all learners. Consequently, when teachers tentatively tried out reform practices, classroom experimentation was reinforced by perceptions of student learning, and teachers took up these changes into their practice. Ultimately teachers in these and other studies of asset-based approach to students changed their beliefs, realizing students were capable of more sophisticated and nuanced ideas than many teachers anticipated (Chen et al., 2019; Davis & Palincsar, 2023; Hanley et al., 2020; Lehrer & Schauble, 2012; Lewis et al., 2015; NRC, 2012; Sandholtz & Ringstaff, 2014; Suárez, 2020). Yet, most of this literature does not dive deeply into *how* and *why* teachers' observations of student assets differentially drive teacher change.

Our analysis is thus predicated on the idea that teacher learning in PD occurs in iterative interactions between exposure to new ideas in PD (activity domain); teacher knowledge and beliefs about pedagogy and students (personal domain); and enactments in classroom instructional practice (practice domain) (see Figure 1). We will systematically examine how these interactions relate to variations in instructional change, with a particular focus on how teachers attend to student ideas and sensemaking related to science phenomena in response to reform practices (domain of consequence). The following research questions guided our study:

- 1) How do teachers vary in their understanding and implementation of reform-based science pedagogies, and overall instructional change after the first academic year of long-term science PD (establishing a continuum of change)?
- 2) What interactions among the domains of professional learning (IMTPG model) contribute to these variations?
 - a) In teachers' perception, what domains play a central role in supporting or stymieing their professional learning and instructional change during PD?

- b) Given the centrality of the domain of consequence (teacher noticing of student ideas), how does this domain function to support teacher learning? That is, how does teacher noticing within the domain of consequence shape their learning in other domains, and how do these interactions together contribute to variation in teacher change?

3 | METHODS AND DATA SOURCES

3.1 | Research design

3.1.1 | Professional development (PD) context

The PD that formed the foundation for this study, the Science Learning Partnership (SLP), a pseudonym, worked with third through fifth grade teachers across eight partner districts in a large, West Coast metropolitan area from 2019 through 2022. Districts were recruited through existing relationships and other forms of outreach. Within partner districts, teachers were recruited through their principals. The approach of the SLP was built on years of research-practice partnership, which established the importance of multileveled communities of practice for effective and sustainable reform (Bae et al., 2016; Hayes et al., 2020; Roth et al., 2011), in addition to adult-level science content and pedagogical instruction. The overarching goal of SLP was to build both instructional and organizational capacity for three-dimensional, NGSS-based science education with a focus on equitable sensemaking discourse. Sensemaking is a dynamic process in which students draw on their own lived experience (Eastwell, 2002; Upadhyay, 2006; Yager, 2000), that is, the broad diversity of knowledge gleaned from everyday activities with immediate and extended family, peers, and community, along with classroom inquiry, as they develop, revise, or critique an explanation or model to understand the mechanisms underlying a phenomenon (Lemke, 2001; NRC, 2012; Odden & Russ, 2019). In sensemaking discourse, academic and everyday languages are used by students to build on one another's ideas (Miller et al., 2018; Suárez, 2020). In equitable sensemaking discourse, students and teachers elevate and value the ideas of diverse and historically marginalized students (Bae et al., 2021) through their implementation of reform practices.

Teachers were invited to participate in SLP for 3 years, each year comprising a weeklong summer institute and three Saturday workshops (Roth et al., 2011; Zwart et al., 2007). Teachers engaged in activities and learning similar to the target instructional practices (Loucks-Horsley et al., 2010), with adult-level content taught using reform practices by a team of university science faculty, instructional coaches, and teacher leaders, and additional pedagogical instruction and reflection facilitated by county science instructional coaches. Pedagogical protocols to support multilingual learners included Summary Tables (Windschitl et al., 2018), KLEWS charts (Know, Learn, Evidence, Wonderings, Science Concepts) (Hershberger & Zembal-Saul, 2015), Say Something and other protocols from Doing and Talking Science (MacDonald, et al., 2016), and practices from Talk Moves for Productive Discourse (Michaels & O'Connor, 2012). Most of the teachers also participated in lesson study (Lewis et al., 2006), a community of practice in which small groups of grade level teachers planned a lesson, observed one another teaching the lesson, and analyzed student work to make revisions for the next round with the support of a PD facilitator. Teachers joined the project in two cohorts, 63 starting in year one, and 26 starting in year two.

3.2 | Instruments and data collection procedures

As part of the project, teachers were asked each year to select a science lesson for researchers to observe and video-record, in which they sought to implement aspects of equitable sensemaking discourse and the science practices of modeling and explanation (NGSS Lead States, 2013). Following the lesson, teachers were interviewed (40–60 min) using a semi-structured protocol that allowed the researcher to follow teacher thinking and probe where necessary. The interviews were audio-recorded and transcribed.

This study primarily draws on the interview data, selected as the main data source for this study because interviews directly focused on teachers’ understanding of reform practices and their attempts to enact them. The first set of questions focused on the observed lesson. Teachers were asked to reflect on successes and challenges within the lesson. They were asked to describe how the lesson fit into a unit or sequence, to generate a record of how the teacher planned to weave the lesson into a longer storyline (Roth et al., 2011), and their plans to include reform practices over the course of the lesson or unit. The second part of the interview focused on teacher understanding of the instructional outcomes of the PD project. For example, in terms of the outcome of discourse, teachers were asked to describe how sensemaking discourse manifested in the lesson, the pedagogies by which they supported student sensemaking, and how they were building a culture for discourse in their classrooms. Then they were asked to describe, as if speaking to another teacher, an ideal moment of science discourse. These questions elicited teachers’ understanding of each main pedagogical outcome, and their perceptions of how they implemented each outcome in practice. The interviewer continued to probe until adequate information was obtained to categorize teacher change (Enderle et al., 2022; Justi & van Driel, 2006; Schipper et al., 2017).

Finally, teachers were asked how they changed their practice for each outcome over the course of participation in SLP, and which aspects of SLP, if any, influenced their change. Subsequent questions addressed the barriers and supports for teaching science in the ways they described, to document how contextual factors shaped such change. The interview was thus attributional in nature. We asked teachers to attribute their pedagogical decisions and instructional change to particular sources or processes, including, but not solely, SLP PD (Huberman & Miles, 2002).

Researcher memos from the observed lesson were treated as a secondary data source. Within 24 h of each observation, researchers completed a structured memo with their reflections on the lesson. The researcher described the nature and extent to which they observed the target instructional practices, noting differences between their own perceptions and those gathered during the interview.

3.2.1 | Sample

Each year of the project we collected data from all teachers who were willing to be observed teaching a lesson, a total of 43 interviews over the first 2 years. For this paper, we selected teachers who had participated in SLP for at least 9 months ($N = 21$) to obtain a detailed view of how teachers were progressing after the first academic year of PD. These teachers all had engaged in at least 50 h of SLP professional development ($M = 95$ h). Due to the COVID-19 shutdown during the second year, Spring 2020, we did not have an accompanying instructional video for four of the sampled teachers. These teachers were interviewed shortly after schools moved to remote instruction, and were asked to think of their last in-person science lesson. School demographics are displayed in Table 1. Teacher demographics displayed in Table 2 illustrate the degree to which the sample is representative regionally. Our sample includes slightly more females than regionally representative of the teacher population, and ethnic diversity skews

TABLE 1 School district demographics.

District name	Enrollment	% English learners	Largest ethnic group	% FRL
Helmwood	21,900	35	Hispanic	73
Mt. Danworth	32,000	25	Hispanic	55
San Loredo	8700	34	Hispanic	65
San Isabela	12,300	28	Hispanic	69
Natchez	12,600	24	Hispanic	50
Jersey	6300	25	Hispanic	54

TABLE 2 Sample teacher demographics.

Gender	Ethnicity	Ethnicity of teachers in county*	Ethnicity of students in the county (for comparison)*	Grade Level
Female 19 (90.5%)	White 10 (47.6%)	61.1%	17.4%	Grade 3 8
Male 2 (9.5%)	Afr-Amer 2 (9.5%)	8.5%	9.9%	Grade 4 6
	LatinX 5 (23.8%)	11.3%	34.0%	Grade 5 7
	Asian 3 (14.3%)	10.8%	26.0%	
	Other 1 (4.8%)	8.3%	12.6%	

*Education Data Partnership (2019).

more toward the ethnic representation of the student population than to the teaching population in the county. School district and teacher names are pseudonyms.

3.3 | Analysis

3.3.1 | RQ1: Categorizing teacher change

To document the degree to which teachers changed their understanding and implementation of pedagogical principles and specific strategies for equitable sensemaking, we analyzed teacher interviews and post-lesson memos for: (1) understanding of PD practices and principles; (2) implementation level; and (3) degree of perceived change (Franke et al., 2001; Grossman et al., 1999; Justi & van Driel, 2006; Longhurst et al., 2017; Schipper et al., 2017). The analysis was both a priori and inductive (described below), and resulted in four categories of teacher change: Static, Initiating, Advancing and Nuanced (Table 3). To triangulate the placement of teachers for RQ1, every interview and related researcher memo were coded by two of the authors. The placement of each teacher along the continuum was discussed to resolve discrepancies and refine the coding process.

- 1) *Understanding of PD practices and principles* (Grossman et al., 1999). We coded interview segments where teachers described their understanding of each outcome. This coding resulted in analytical documentation of the ways each teacher described overall PD-aligned pedagogical principles (e.g., sensemaking), as well as specific strategies, such as students doing gallery walks (small group review of others' work), or using a KLEWS chart (Hershberger & Zembal-Saul, 2015). For example, Initiating teachers used the words associated with particular instructional strategies (e.g., "I used KLEWS"), but still needed to develop a thorough understanding of the pedagogical principles that underlay such strategies. Among Advancing and Nuanced teachers, descriptions demonstrated alignment with social constructivist and culturally-relevant pedagogical principles that were explored in the PD (Moje et al., 2004; Morales-Doyle, 2019; Windschitl & Stroupe, 2017). Such alignment better allowed teachers to adapt tools and strategies to meet the needs of classroom and organizational contexts (Grossman et al., 1999; Longhurst et al., 2017).
- 2) *Implementation Level*. We gauged teachers' implementation level from their interview and post-lesson researcher memo. The memo provided a starting point for identifying the teacher's implementation level according to the boundaries described in Table 3. The interview provided important additional data regarding how the teacher situated the lesson in a unit, so that the observed lesson was not treated in isolation (Roth et al., 2011). To identify levels, we adapted the implementation levels described by Grossman et al. (1999) as "levels of appropriation" modified by our emergent findings (see Table 3 for descriptions of the levels).

TABLE 3 Ordinal change categories and descriptions.

Change Category	Description
Static change	Understanding/beliefs -- PD practices and principles. Teachers in this category: • Misunderstand pedagogical principles and practices. • Describe teacher-centered, transmission approach to teaching. • Perceive science as imparting knowledge, supported by hands-on activities. Implementation level (<i>Appropriating a label; Grossman, 1999</i>). Teachers in this category: • Discuss trying to implement student-centered practices, but when challenged, default to a teacher-centered approach. Degree of perceived change. Teachers in this category: • Discuss struggling to change even surface-level instructional practices, or do not understand them enough to reflect on their degree of change.
Initiating change	Understanding/beliefs--PD practices and principles. Teachers in this category: • Understand only surface-level features of pedagogical practices and strategies. • Express misgivings and anxiety about skill level with new practices. • Exhibit uneven alignment with pedagogical principles. Implementation level (<i>Appropriating surface features; Grossman, 1999</i>). Teachers in this category: • Experiment with tools, strategies, and formats mechanistically or superficially. • Exhibit surface level implementation of strategies while moving toward alignment with pedagogical principles. • May embrace a pedagogical concept, but are stymied when students become stuck. • Implement SLP strategies on top of existing, non-aligned curricula. Degree of perceived change. Teachers in this category: • Described tentative use of new student-centered discourse strategies or science-specific pedagogies, such as modeling.
Advancing change	Understanding/beliefs--PD practices and principles. Teachers in this category: • Discuss how PD principles and strategies resonate with their existing instructional beliefs and some existing routines. • Generally describe a student-centered approach to teaching. Implementation level (<i>Appropriating surface features; appropriating conceptual underpinnings; Grossman, 1999</i>). Teachers in this category: • Actively apply pedagogical strategies from PD • Willingly experiment with conceptual underpinnings and adapt them to current context, although they occasionally veer towards using tools without underlying pedagogies (Longhurst et al., 2017, p. 6) • Actively support student sensemaking and discourse. Degree of perceived change. Teachers in this category: • Describe making purposeful instructional shifts, sometimes managerial or structural in nature, but, nonetheless, student-centered. • Discuss how they transitioned away from directing student conversations, and toward facilitating a freer flow of ideas. • Talk about beginning to recognize that a socially- negotiated space (Chen, 2019) for peer-to-peer discourse is critical to the development of student-directed investigation.
Nuanced change	Understanding/beliefs--PD practices and principles. Teachers in this category: • Show deep understanding of pedagogical principles • See students as co-constructors of scientific knowledge. • Discuss how tools and strategies introduced in PD resonate with their existing beliefs. • Quickly develop understanding of new strategies. Implement level (<i>Appropriating conceptual underpinnings; achieving mastery; Grossman, 1999</i>). Teachers in this category: • Adapt pedagogical principles from PD to their classroom context. • Adjust existing routines to better facilitate student equitable sensemaking discourse. • Base lessons on SLP content and strategies as the backbone of the curriculum. • Express confidence with integrating existing resources occasionally as needed. Degree of perceived change. Teachers in this category: • Talk about changing their approach to classroom culture, integrating students' productive struggle to make meaning of scientific phenomena. • Describe implementing SLP pedagogical strategies pervasively, and with thoughtful, pedagogically-aligned adaptation in their classrooms. • Are sometimes explicit about strategies they have not yet implemented; perceive their shifts as works in progress.

TABLE 4 Ordinal change categories and teacher data.

Change category	Number of teachers	Average Hrs in SLP PD	Average Hrs in other science PD	Average years experience
Static teachers	4	89.5	9.3	15.0
Initiating teachers	7	120.6	6.9	18.9
Advancing teachers	5	91.5	8.4	12.4
Nuanced teachers	5	119.9	28.4	18.4

3) *Degree of perceived change.* We analyzed aspects of the interviews where teachers were asked to describe their degree of change in understanding and implementation since the beginning of the PD (Justi & van Driel, 2006; Schipper et al., 2017). These descriptions include both accounts of prior teaching practice in contrast to current teacher practice (e.g., “I used to think students' heads needed to be filled...”) and accounts of new implementation (e.g., “I tried the KLEWS chart for the first time...”). Table 3 summarizes the salient features of change categories, and Table 4 lists their distribution among the sample.

3.3.2 | RQ2: Coding for the role of professional learning domains in teacher change

Interview transcriptions were coded by two authors on the project, using the a priori domains of teacher learning (Clarke & Hollingsworth, 2002) (Figure 1): the personal domain, practice domain, activity domain, and domain of consequence. Emergent codes were added within domains to understand how each functioned in the local contexts of the teachers' professional practice. Excerpts started at the beginning of a discussion of any given domain, and ended when the topic changed. To ensure reliability, two authors engaged in a co-coding process wherein each coded a particular interview, discussed the discrepancies, finalized the coding of the interview based on consensus, and refined the codebook. This process was repeated across four interviews. Code matching between two raters was initially 70%, rising to 95% over the four interviews. Following this level of agreement, one author coded 10 interviews, while the second author double-coded to review the coding, including noting additional discrepancies. These, too, were discussed to establish full agreement. Finally, the first author coded the remaining seven interviews.

To answer RQ2a, we first used Dedoose software to document the number of times each learning domain was mentioned in the data set in relation to pedagogical decisions or instructional change. We used this as a rough indication of centrality because of the semi-structured, qualitative nature of the interviews. To further document the centrality of the domains, we examined code co-occurrence (i.e., the number of times codes in each domain were applied simultaneously with other domains, indicating an intersection between one domain and another). For example, one teacher described an activity about size and distance in the solar system. She stated, “I thought that by giving them different sized papers [it] would kind of get them into that thinking...but they couldn't figure out what size they needed and why.” This excerpt was coded with both a subcode of *domain of consequence* (student characteristics) and a subcode of the *practice domain* (reflections on implementation).

3.3.3 | RQ2b: Coding within observations of student learning

Because of the salience of teacher observations of students (domain of consequence) in RQ2a, we conducted a follow-up analysis on all segments of text specific to teacher observations of students, with the goal of understanding how this domain functioned as a driver of teacher learning. We used the constant comparative method (Huberman & Miles, 2002), to generate themes in this area, in which segments representing unique or



similar patterns were aggregated. We examined how noticing played a role in each theme across change categories. We distilled the data to three predominant themes that showcased how and why teachers varied in their uptake and implementation of PD: (1) relating pedagogy to student learning; (2) student engagement and productive struggle; and (3) student assets. We compared final themes to the transcripts over a third reading by each researcher, and wrote short narratives of the theme characteristics for each change category (see Table 3). During this process, we noted relationships between domains that were integral to each theme. For example, in Theme 1, Static teachers had difficulty connecting student learning to their instructional practice, while teachers in the Nuanced category more often made changes in practice based on what they perceived students doing, and persisted until students developed mastery with reform-based approaches to science teaching and learning from SLP. For both sets, interactions emerged between teachers' understanding of and ability to implement strategies from the PD (activity domain), teachers' connection of student learning to such strategies (domain of consequence), and how they changed their knowledge and beliefs about possible student learning (personal domain).

3.4 | Limitations

There are several limitations of this study worth noting. First, we did not observe lessons or interview teachers before their participation in the PD. Therefore, the descriptions of teacher change are based largely on teachers' own first-hand accounts of changes in their practice and beliefs (Erickson, 2011), corroborated through researcher memos following the observation. Second, although all observed lessons were video-recorded, the onset of the pandemic and subsequent move to remote instruction for all participants in the middle of the second year prevented observations of four of the sampled teachers. These teachers were asked to think of their last in-person science lesson when responding to interview questions. Subsequent studies would benefit from robustly accounting for teacher change through pre- and post-interview and classroom observations. Third, owing both to the goals of the grant, and to the ethnic diversity of students and teachers in the region where the study took place, our findings may not be entirely generalizable to teachers and classrooms across all geographic areas of the country. Although our findings were resonant with many other studies, the unique features of this study (combining noticing with domains of teacher change) would benefit from replication elsewhere.

4 | FINDINGS

4.1 | RQ1 - Categorizing teacher change

To understand how and why teachers differentially change in PD, we first needed to determine variation in their change. After analyzing the data as specified above, sampled teachers were placed into change categories. We anticipated that differences in years of experience might have a relationship with change categories. Also, because hours spent in PD are linked to changes in instructional practice (Darling-Hammond & Richardson, 2009; Yoon, et al., 2007), it follows that differences in PD hours might also relate to degrees of teacher change. Yet, as demonstrated in Table 4, there appeared to be little relationship between change category and years of teaching experience or SLP PD hours. Teachers in all categories had an average of more than twelve years teaching experience (ranging between 5 and 29 years). By the 9-month mark, teachers in all categories had participated in an average of over 89 PD hours, exceeding the 30-h threshold linked to the most significant improvements in student learning (Yoon et al., 2007). This indicated there might be other influences on teacher change (the focus of inquiry of RQ2a and 2b). The only clear pattern was between change category and hours of *external* PD (before the start of SLP). This data is from a survey, and is defined as PD provided by sources other than SLP and its affiliate university. While it may have supported teacher noticing, the nature of the external PD is not the focus of this paper.

4.2 | RQ2a - Central domains of teacher change

We analyzed the corpus of data using the four domains from the IMTPG model to understand how each domain functioned to support or stymie instructional change for SLP teachers within this particular context. Salient emergent characteristics of the *personal domain* consisted of the teacher's knowledge and beliefs, and their alignment (or not) with the PD, teachers' pedagogical principles, teacher experience, teacher affect, and dispositional characteristics. Emergent characteristics of the *activity domain* included the importance of pedagogy, content, and resources learned or obtained in the PD, the role of lesson study (Lewis et al., 2006), and the professionalism accorded teachers by PD facilitators. The *practice domain* encompassed teacher descriptions of teaching in their classrooms, including experimentation with strategies learned in PD, reflections on implementation, and integration of other content standards with science. Emergent aspects of the *domain of consequence* consisted of teacher perceptions of student abilities and characteristics, teachers' remarks on student affect and excitement, and their noticing of student learning. These are explicated more thoroughly in other papers (e.g., Hayes et al., 2023).

To understand the centrality of the learning domains in teachers' perceptions, we first examine the number of times each domain was coded as present in the sampled data in relation to descriptions of implementing strategies from the PD or instructional change (Table 5). The domain of consequence was most present in the data (774 excerpts), followed by the personal domain (674 excerpts). Second, we documented instances of code co-occurrence (Table 6). Both the domain of consequence and the personal domain intersected highly with other domains of learning (1085 and 1088 co-occurrences respectively, 596 of co-occurrences being between these two domains; Table 6). The greatest areas of co-occurrence between the domain of consequence and subcodes of each domain were teacher beliefs (personal domain; 366 co-occurrences), uptake of strategies from the PD (activity domain; 151 co-occurrences), and reflection on instructional practice (practice domain; 160 co-occurrences). The qualitative analysis of evidence in RQ2b documents how interactions between domains played out within these co-occurrences.

Overall, analysis of our data showed that the domain of consequence was central to teachers' description of their changes in instructional practice and interacted heavily with other domains. Therefore, in the following section on RQ2b, we qualitatively examine what is happening in the domain of consequence, including the ways teachers notice student learning, and we document the relationship between noticing and other domains of teacher learning (Figure 2).

4.3 | RQ2b - How the domain of consequence functions as a driver of teacher learning

4.3.1 | Theme 1: How teachers relate student learning to pedagogy

Moving from disconnection between students and pedagogy (Static) to reflective shaping of instruction based on student response (Nuanced)

4.3.1.0.1 | *Static*. Two of the Static teachers were long-term science specialists, and, hence, started the PD program with high content knowledge. Yet, when teachers in the Static category were asked about instruction,

TABLE 5 Excerpt occurrences by domain of professional growth.

	Personal Domain	Activity Domain	Domain of Practice	Domain of Consequence
# excerpts coded	674	422	274	774

TABLE 6 Code co-occurrences between each of the four domains of professional growth.

	Personal domain	Activity domain	Domain of practice	Domain of consequence	Totals
Personal domain		328	164	596	1088
Activity domain			104	239	671
Domain of practice				250	518
Domain of consequence					1085

none of the four described attending to student sensemaking in relation to their instructional practice. Common across the category was a tendency to describe their own actions along with a simplistic narrative of student activity (Barnhart & van Es, 2015). In a typical example, Margaret described an activity from SLP (watching bread mold) and her interpretation of what the students did (“we made a grid”), but stopped short of any reference to discourse or descriptions of what students were learning.

...they did things to bread and stuck them in plastic bags, numbered them. What do you think is going to happen? Make your best guess... What did you notice? Then we made ... a grid and we could graph how many percent of it was yucky. ... the one that the kid licked on... It was the absolute worst...

Margaret also conducted assessments without noting what students understood.

They were supposed to write day 10 of observations, which one is the worst, which one's the least, which one made the biggest change... Well, it turns out the one who noticed [the most bacteria growth] was correct... That's the way I got my assessments. I quietly threw away all those little pieces of paper.

Privileging the canonical “right answer” (Barnhart & van Es, 2015; Colley & Windschitl, 2016) Margaret discarded all other student ideas posted on the classroom KLEWS chart, shutting down discussion and effectively denying other students’ participation in knowledge building. As a result, she also deprived herself of an opportunity to learn by leveraging their thinking (Colley & Windschitl, 2016; Luna & Selmer, 2021).

In addition, although Static teachers attempted to implement some strategies they learned in PD, all spoke of fact accumulation as the primary evidence of students learning science. For example, in the following quote, Ann spoke about students’ use of science vocabulary (Lee et al., 2019) as evidence they understood the role of clouds as weather phenomena: “We used clouds. We talked about clouds going to and from recess for weeks on end...we learned all the names of the clouds like cumulonimbus and, and stratus clouds...”

4.3.1.0.2 | Initiating. Initiators were more likely than Static teachers to connect student learning with their instruction. However, they vacillated between teacher-controlled and student-centered learning (Stroupe, 2014), and were at times unable to notice how teacher moves and teacher-initiated structures inhibited their ability to perceive student thinking. For example, Maxine described her regrets about not providing sentence frames to support cause and effect reasoning, especially for language learners: “I know one thing I could have done...is give them more sentence frames...‘When I did this, then that happened.’ That...[cause and effect] statement is very difficult for them to understand...” However, Maxine went on to describe that when students engaged in dialog regarding their jumping frog models, “[They] did talk to each other about the fact that, ‘I had a small rubber band, and it jumped higher...’” The student she was quoting was engaging in cause-and-effect reasoning, yet, Maxine was disappointed, saying, “So if I had given them that type of sentence frame, maybe they would have been able to put...”

[the] pieces in." Even though Maxine described students' cause and effect reasoning, her perception that she needed to shoehorn their explanations into a prescribed structure precluded attending to the substance of ideas and how their relevance might have been amplified (Stroupe, 2014; Windschitl et al., 2012). In effect, over-thinking a protocol, instead of adjusting it to meet her students' needs, undermined her noticing of students' engagement with meaningful content and substantive understandings.

In the Initiating category, teachers often mechanistically applied SLP strategies and tools, which neither capitalized on students' curiosity, nor resulted in an organic teacher response to what students understood about the science. Lucy was excited to have new strategies to take away from the PD, but in a lesson on relative size and distance in the solar system, she tried applying a SLP math integration without a deep understanding of the process or a clear connection to the students' prior understandings. She said:

So they were having a hard time making that connection...I thought that by giving them different sized papers [it] would kind of get them into that thinking...but they couldn't figure out what size they needed and why... They could easily label it, but they didn't get the scaling...

Lucy was uncertain over how to scaffold the three-dimensionality of a math integration (Luna & Sherin, 2017; Windschitl et al., 2012). When students became frustrated by the complex task, Lucy led them toward correct answers, a retrenchment into her prior teacher-centered practice. She noticed that students were not understanding the task, but was unable to adjust in real-time to keep the lesson optimally structured for student engagement in three-dimensional science learning.

4.3.1.0.3 | *Advancing*. All five Advancing teachers were more likely than Static or Initiating teachers to attend to student sensemaking and interpret the impact of the SLP strategies they incorporated into their instructional practice. Farah described her students using models for sensemaking:

My students were able to... show what they know. They got to describe it. They got to draw their thinking, to label, to work it out with their partner... have a discussion...put their ideas together, and come to a consensus model. And it's like, "Here's my evidence of everything that I've learned. It's all right here..."

As teachers in the advancing category discussed interpretations of student understanding, they simultaneously made purposeful shifts in their instruction. For some Advancing teachers, such shifts were managerial or structural in nature (Russ & Luna, 2013), but were nonetheless centered on students, rather than the teacher. Erin's lesson provided an excellent example of a structural change as students continued working on their bridge models instead of engaging in the discourse she had planned. In-the-moment, Erin made a structural change by inviting students to sit down at the rug, away from the hands-on activity, so they could listen to one another talk about how models changed their thinking.

4.3.1.0.4 | *Nuanced*. All five Nuanced teachers described in detail how they attended to and interpreted students' sensemaking of relevant science ideas in relation to their instructional moves. Emily recalled a student "cementing" conceptual connections around cloud formation as the class engaged in SLP activities, including a cloud-in-a-bottle activity:

[The student said,] "Low pressure and high pressure." I thought, that's amazing. I didn't get that when we [teachers at the PD] did it. [The student said,] "Well, you need low pressure, because when we let go, that's when the cloud formed."



Emily interpreted this as a breakthrough in the child's sensemaking, and made her thinking public, a response critical to student learning (Luna & Selmer, 2021; Roth et al., 2011). During her interview, Emily relived the moment, "That was super awesome! Her group was like, 'Whoa. What? Pressure?'" Emily's in-the moment classroom response (Jacobs et al., 2010), elicited by her noticing that students had arrived at a new conceptual understanding, legitimized the student's idea, and was further reinforced by her peers' excited reaction.

Unlike teachers in other categories, Nuanced teachers' interpretations (Jacobs et al., 2010) of the diversity of students' academic understanding led them to adjust PD pedagogies continually and align them with student discourse, rather than simply to remove structural impediments, as did Erin in the Advancing category. Lydia, e.g., recalled how during one lesson, ideas about camouflage came up in student conversation, and she wanted to ensure they understood the meaning. However, Lydia's concern went beyond vocabulary assessment. She perceived students were dancing around the edge of a novel idea. She said, "I would have stopped it very easily a couple of years ago, 'Oh, it was camouflaged. Okay, good. We got it.' And now it's like, 'No, that's not exactly what I'm going for...'" She continued to draw out students' thinking to elicit understandings of reproduction as an aspect of inheritance. Nuanced teachers' noticing of student learning needs and sensemaking was more sophisticated than that of teachers in other change categories, and resulted in complex and subtle changes in instructional routines, as well as adaptations of SLP strategies. Lydia said:

Explaining their thinking is the hardest thing for them to do... But again, the sentence frames can't be so narrow that they're just filling in, because...when I make it so narrow...I take away...their independent thinking... then they're trying to conform their thinking to the frame.

4.3.2 | RQ2b theme 2: Teacher view of student engagement and productive struggle

Moving from focus on student affect (Static) to students' productive struggle (Nuanced)

4.3.2.0.5 | *Static*. When students wrestle with puzzling phenomena, they often come away with both novel understandings of science concepts (Lehrer & Schauble, 2012) and uncertainty about how their observations fit with what they already believe about science (Chen et al., 2019). In this study, we use the term "productive struggle," to describe how students experience dissonance between new phenomena and prior knowledge, grapple with scientific uncertainty (Manz & Suárez, 2018), and negotiate the social space where they can engage in argument to arrive at consensus among peers (Chen et al., 2019; Manz & Suárez, 2018).

None of our four Static teachers described student engagement in productive struggle or attended to how students grappled with science uncertainties. Instead, as teachers learned both the content and pedagogy taught in PD, they verbalized their own sensemaking. Ann, for example, focused on her own connections between ideas: "We were talking about hurricanes in the news... why they occur near the equator, and we were talking about the water cycle before that, so it all just kind of went together." When asked about student sensemaking in the lesson, Sharon shrouded hazy perceptions of science learning in pedagogical jargon.

...I have seven different languages spoken in here... tak[ing] all of those things under consideration, the teams really looked good...being able to scaffold each other, the zone of proximal development was...in there. I think that all of that facilitated them being able to have some real discourse about what was going on.

Sharon was excited for students to engage with the lesson, but she was ambiguous about the science concepts she thought they were learning.

When Static teachers did describe their students' response, all four discussed affect, that is, enjoyment of activities, rather than how students made sense of phenomena (Jacobs et al., 2010; Luna & Sherin, 2017). Ann described, "[the students] had...to tell me whether they thought it [the cloud] was real or fake...they got a kick out of that activity...it's like magic tricks work better for them." Like all Static teachers, Ann promoted enthusiasm for the lesson, but did not reflect on how the children connected cloud formations with weather features.

4.3.2.0.6 | *Initiating*. Initiating teachers' perceptions of student engagement and productive struggle reflected a range of noticing skills. Like Static teachers, some Initiating teachers attended primarily to student affect. As an example, Lucy described her students' enthusiasm: "I'm dealing with a group of kids that didn't have...good hands-on science for an entire year and so almost any little thing blew their mind." Maureen similarly said, "Once you put up that question... like, all of a sudden, they're very curious."

Others began to attend to student content ideas as their classrooms became less teacher-directed and more student-focused (Stroupe, 2014). This set of teachers described trying to support meaningful connections across content areas, but often felt students were not engaging productively to integrate new information. The teachers themselves were uncertain in how to scaffold complex discourse (McNeill & Knight, 2013; Windschitl et al., 2012), and did not persevere. Maxine described the proportional reasoning she wanted students to consider, but they were engaged in a lively building activity, and ignored Maxine's call to connect the science with their recent math lesson:

I was trying to get them to understand that maybe the proportions needed to be [changed]...so I go, "Okay, you guys are wanting to make it bigger... so what's going to happen if you change the measurements?" And I don't think they got to that piece.

Unsure how to build on the class's knowledge about proportions (Kang & Anderson, 2015; Windschitl et al., 2012), Maxine allowed the learning opportunity to pass, thus, interaction between the domains of consequence and practice did not occur, and her opportunity to be informed by the interaction was also lost.

A third set of Initiators attended to how students used new strategies to resolve uncertainties, and perceived a more direct path from productive struggle to conceptual learning. Katarin explained how students' use of models, for example, elicited their deeper thinking. "The curiosity was there more, and looking at their own models made them able to ask more questions about moving it forward." Without giving away answers, she "primed" the conversation (Windschitl et al., 2012) to encourage whole-class discussion:

Getting them to figure out that Earth and the inner planets are so much closer together, then looking at the size, the difference between space...we're like, "Well, is there any correlation between the sizes of them...? And is there any relationship between why they're so big and the distance?" And [then] they were able to ask questions about that. "Is that why? They're farther apart because they're bigger...?"

Instead of delivering an explanation, Katarin began to "shape" (van Es & Sherin, 2021, p. 24) the conversation, scaffolding access to the crosscutting concept of cause and effect.

4.3.2.0.7 | *Advancing*. As in previous categories, Advancing teachers still described student affect, but, like Erin, recognized that a socially-negotiated space (Chen et al., 2019) for peer-to-peer discourse was critical to a classroom culture where students could wrestle with new ideas and take ownership of their explanations:

...the kids have a model and then they kind of get stuck, and the other kids will say, "Well, did you mean...?" to kind of fill in what they think they're seeing... And they're like, "Yeah, yeah!" So, I think



the advantage is...kids take ownership, and I think they have a deeper understanding of whatever topic it is we're talking about...then they start applying it to different areas as well.

In this example, Erin's interpretation was substantive, rather than structural (as in the example described in Theme 1; Russ & Luna, 2013), especially as she noticed that her students' sense of ownership began to emerge in other content areas.

Advancing teachers were able to integrate SLP pedagogical strategies more seamlessly than their Static and Initiating peers, and when students were free to exercise agency in expressing their ideas, they noticed students became better science thinkers. Tess said,

One of the [SLP] strategies that I really feel is successful is when we're all in productive struggle, when we see a group that is getting a hook in something, that we fishbowl or do a gallery walk to really see, well, "Who else is latching onto this?" ... And it's really effective at keeping the teacher out of it.

Like Erin (and unlike Static and Initiating teachers), Tess perceived her students were learning more by talking with one another than with the teacher. This reinforced her growing pedagogical beliefs about student centered instruction (personal domain).

4.3.2.0.8 | *Nuanced*. All five teachers in the Nuanced category shared complex noticing of students' productive struggle. Unlike teachers in other categories, they rarely described general affect, but rather, interpreted specific examples of children making sense of how and why phenomena occurred. Emily recalled:

It's so fun when they're disagreeing with each other and it's because they're talking about two different aspects of the same thing. Like the pressure versus evaporation. One was like, "No, it has to come from the water," and "No, you need low pressure." It's like, "Well, you need both. You're both right." ...Nothing's one-dimensional.

Nuanced teachers noticed that the more students persisted through their cognitive dissonance to understand science phenomena, the more they had to talk about, sometimes with unanticipated manifestations, as Emily reflected:

When kids are thinking, they physically squirm. To me that's that aspect of really good discourse, is when they're looking at each other just after someone has said something, and they're like, "I don't know if that fits yet and I need to talk to you more about it." ...I'm just in love with that concept...

Lydia, too, reflected on supporting productive struggle:

I want the kids to get as much out of their experiences as they can, and if it means leaving them in dissonance on an idea, I am all for it. The "I don't know" idea is very powerful in getting the kids to be curious and search for meaning.

Nuanced teachers provided precise descriptions of how students' use of science practices, like constructing a model (learned in SLP), produced authentic discourse. Gil provided evidence that he knew his students were learning from this process, as well as from one another:

...one “ah-ha” moment for me was when...I saw students arrange the sort, and it had nothing to do with [what] I was thinking...it's coming from them... So, they do the struggling...they try to figure out what's going on, and, at the end, we'll pull it together.

Universally, Nuanced teachers came to believe that discourse routines themselves are not the discourse. As a result of attending to and interpreting students' productive struggle, they realized students talk when they have important things to say.

4.3.3 | RQ2b theme 3: Student assets

Moving from deficit views (static) to leveraging students' lived experience (nuanced).

4.3.3.0.9 | *Static.* Static teachers were split on their beliefs as to how students' ways of understanding the world inside and outside the classroom were salient to science learning, especially among children from “backgrounds and experiences different from those of...their teachers (Moje et al., 2004, p. 41).” Three of the four static teachers appeared bound by the personal belief that children's lived experience was not a valuable source of knowledge to the classroom (Lemke, 2001; Suárez, 2020); the other wasn't sure how to build on such experience to support student reasoning (Windschitl et al., 2012). Sharon, the exception, perceived young learners' knowledge and ideas as valuable to the classroom. She connected with an English learner over his rock collection, providing him a pathway to practice early language skills. She said,

...even my kid who came in not speaking...late last month was the first time he actually...spoke out loud... He...brought a geode that he got from Great America... he was so excited that we're getting into rocks. I'm really happy that he's feeling empowered to use his physical voice now.

Sharon interpreted student curiosity as a valuable asset that could support science learning. She continued, “I have seven different languages spoken in here...They're all on the same level playing field when it comes to the language of science...seeing the language develop, I think that they're all feeling, ‘I'm not an outlier...’” Sharon supported discourse using a variety of language acquisition strategies (Lee et al., 2019), but it was not yet clear how she planned to leverage their full communication repertoires (Suárez, 2020) to ensure all students expressed their science ideas and prior knowledge in ways that could “serve as building blocks for productive theorizing” (Colley & Windschitl, 2016, p. 1012).

Margaret and Ann, with high content knowledge, but low belief alignment, perceived students as receptors of teacher knowledge: to them, children's lived experience contributed little value to the science conversation (King et al., 2021). Ann championed the single science-oriented student whose “correct” knowledge added value to the classroom, and thought it acceptable that others “just kind of listened.” The cultures of Static teachers' classrooms advantaged teacher-directed lessons over student curiosity and questions. Reflecting on her practice, Margaret said, “Most of the time I'm old-fashioned. ‘You're an empty slate! Let me fill it up for you!’ Pretty tight labs... pretty structured.” The perception of youngsters as empty vessels, unable to exert agency on the world around them, left teachers to do the meaning-making, the explaining, and the telling, thus depriving children of the opportunity to engage with science ideas on their own terms.

4.3.3.0.10 | *Initiating.* Initiating teachers demonstrated mixed perceptions of students' lived experience. Four of the seven Initiators believed that student prior knowledge and lived experience contributed to their science lessons (Lemke, 2001). Maxine, for example, remembered:



And so, being able to speak in your native language...to bring that knowledge that you have in your own tongue, is what I like... teachers used to tell me what they [students] don't know... No, it's not that they don't know anything...They have it [experience worthy of sharing].

Both Katarin and Carissa observed how learning improved when student experience was treated as worthwhile. Katarin described the importance of a student-directed classroom culture, and the challenge she faced establishing it. She said, "They do a lot of the heavy lifting. It's not so much *us* giving to them now... You want *them* talking about it and doing it. Being excited about it and wanting to be involved." These Initiators believed students needed to *do* science to learn, demonstrating a growing intersection between the personal domain and the domain of consequence. Yet even these four teachers expressed lingering doubts that students had the skill to do the *real* work of science. Maxine perceived that students did not engage one another in meaningful dialog because their language acquisition skills were in development (Lee & Luykx, 2005). The remaining three Initiators persisted in deficit views of students' prior knowledge and skills. Maureen said, "There's not a whole lot they've been through... I think they're doing as much as they can, but they're so little." Her statement encapsulated a general belief among Initiators that the collective contributions of 8-to-10-year-olds were insufficient to be of pedagogical value.

4.3.3.0.11 | *Advancing*. All five Advancing teachers' interpretations of students' lived experience generated positive feedback: the more that students' lived experience was incorporated into the practice domain as a valuable resource for classroom instruction, the more valuable the teacher perceived student views to be (personal domain). Tess, for example, counted on students' agency, that is "the power to shape the knowledge production and practices of a community (Miller et al., 2018, p. 1)" to support the direction and flow of their classroom's discourse:

Well, I think...it's a vital role because they're showing each other that their voice matters. And they get to build a community of taking ownership of your learning. That it's not just...swallowing whatever is happening in the room, that "I'm an active [learner], that I'm shaping the lesson..." Every time they explain their thinking to someone else, they're...synthesizing and crystallizing what it is they actually know.

David, too, spoke of how the contributions from diverse cultures made lesson content interesting for everyone in the classroom. "...I have kids here from quite a few different countries and from different households and...they did bring in their ideas from home. ...their parents were asking me questions on ClassDojo...They love it, and I enjoyed it." Incorporating students' ways of knowing into the classroom culture provided David a sense of personal and professional satisfaction, linking teacher perceptions in the domain of consequence with beliefs in the personal domain. In another example, shared humor over changing a baby's diaper helped David connect with his students' family lives. When they discussed common curiosities, like why it was important to use soap when washing their hands, he was able to link his perceptions of student-constructed learning to changes in his practice.

Yet, four of the five Advancers still expressed uncertainty that students had the skill to conduct their own investigations. Tess was unsure how to respond to student thinking about scientific models:

I feel like we're still developing...having a model helps them refer to something. Sometimes...I'm looking at their model, and I'm thinking, "Say this. Why didn't you put that in your model?" So, I think I'm still...puzzling with how to get more.

Tess saw that not all students were using models to support their sensemaking adequately. She wanted model revision to elicit deeper thinking, but puzzled over how to improve her pedagogy (Windschitl et al., 2012).

4.3.3.0.12 | *Nuanced*. Nuanced teachers attended to students' innate curiosity and provided vivid accounts of the assets children brought to the classroom. Emily reflected:

...a lot of my ELs are Central American... So many of their grandparents own farms. They go down in the summer and help out... some of my ELs that have the most difficulty sharing, were the few that actually knew a pea came from a pod... So then when people were walking around and looking at other ideas, they were like, "How did they know that?" It was just like, yay! Someone new gets to shine.

During students' gallery walk Emily interpreted that, across content areas and units of study, students' lived experience afforded them specialized funds of knowledge (Barton & Tan, 2009; Moje et al., 2004) that reflected their cultural and home experiences. She said:

...there's a lot more storytelling and verbal passing on of information. I think that's a really great strength...one of my kids did a narrative on birthing a cow...but the few that read it were just like, "He birthed a cow? How do you birth a cow?" ...We're not reading it from a book. That's just the way of experiencing the world.

As Kayumova and Dou (2022) point out, "...the notion of equity cannot be reduced to mere knowledge and skills (p. 4)." Rather, it must include "representation, identification, and belonging (p. 4)." Lesley, for example, noticed that students from the dominant culture with traditional science knowledge were more likely to speak up (King et al., 2021). But, instead of championing a typical "star" student's response (as Static Ann did), Lesley publicly legitimized ideas from students who struggled with English fluency and provided space for them to participate in science and exercise their repertoire of communication skills (Suárez, 2020). She recalled an in-the-moment individual response that she then leveraged for the benefit of the whole class (Luna & Selmer, 2021):

So then I challenged him to go out and help other groups solve it [an engineering challenge]. And not all those groups spoke Spanish, but he was [there] with hands and thumbs up and getting other groups [involved]... he didn't really have math skills... And didn't have the language skills and he couldn't write... And all of a sudden, he became this bueno engineer, and his status did rise because the kids now realized he could accomplish a lot.

Nuanced teachers also noticed that, presented with novel problem-solving challenges, students who activated prior knowledge were more likely to figure things out on their own, eclipsing the need for teacher intervention. These noticings precipitated a learning feedback loop between the domain of consequence, the personal domain (new understanding of students), and the practice domain (providing additional opportunities for student agency and activation of prior knowledge). For example, Emily said,

I really wanted to give them opportunities to kind of change how an experiment was set up, play with it, and allow them to answer their own questions... I feel like that's the groundwork for any scientific thought...using whatever words they're throwing out there. So, if they're throwing out fog, then take fog, take ownership of it. If they're talking about evaporated water, fine!

Overall, Nuanced teachers were less likely to perceive that students needed controls when they headed down an unexpected path. Lydia observed her students were better off when she got out of their way, and they could better exercise their constructivist nature:

I get more information...when they go off track than if they're staying right on the path that I chose for them. And kids naturally do things that I don't expect them to do, and that doesn't necessarily mean it's a wrong result, it's just a different result. I've been teaching for thirty years, so I have a certain kind of idea of what's going to happen, but I don't have a planned end point for most things. It's going to go where it goes, I just want them to understand it when they get there.

In creating a more deliberate environment for students to exercise their agency, Lydia acknowledged she was learning from her students' ideas. She recognized that student learning was not entirely within their control even when student agency had precedence, yet she embraced the pedagogical ambiguity and allowed for shifts in classroom norms towards reform practices from SLP.

4.3.4 | Summary - intersection of teacher noticing and domains of professional learning

In this study, we examined what interactions among the domains of professional learning contribute to variations in teacher change (RQ2a), and particularly how teacher noticing within the domain of consequence shapes their learning in other domains (RQ2b). Our study showcases the presence of a series of feedback loops across teacher professional learning domains, in which the domain of consequence acted as a touchstone throughout the iterations. In cases of teachers at the higher end of the change continuum, the iterative process followed a sequence like this example (Figure 3):

- a) Teachers try out a strategy from the PD in their classroom practice.

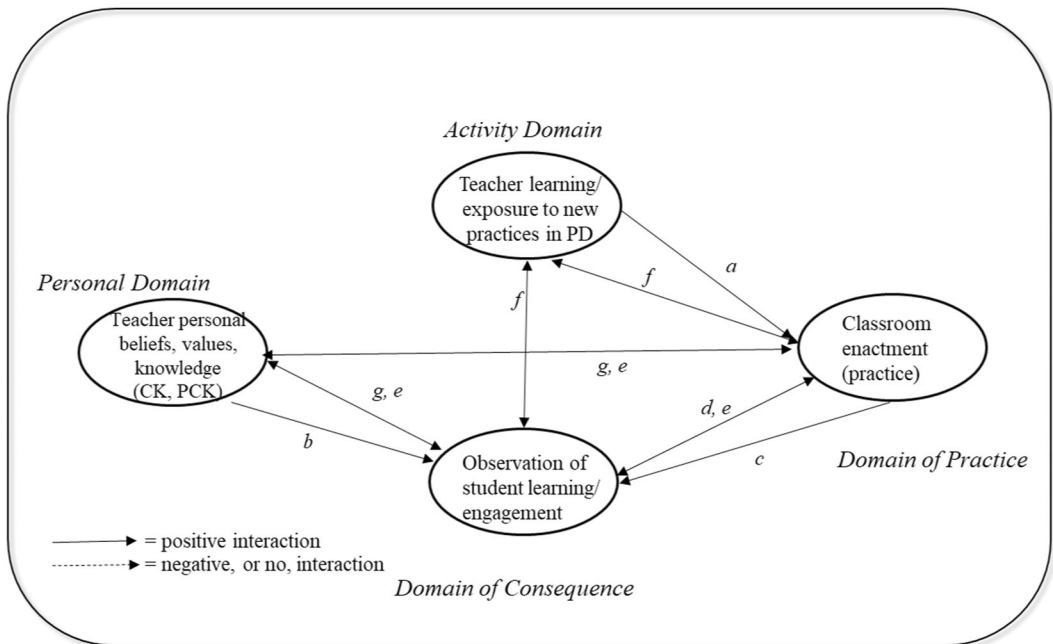


FIGURE 3 Operationalization of the interconnected model of professional (Clarke & Hollingsworth, 2002; Hayes et al., 2019), among advancing and nuanced teachers in PD.

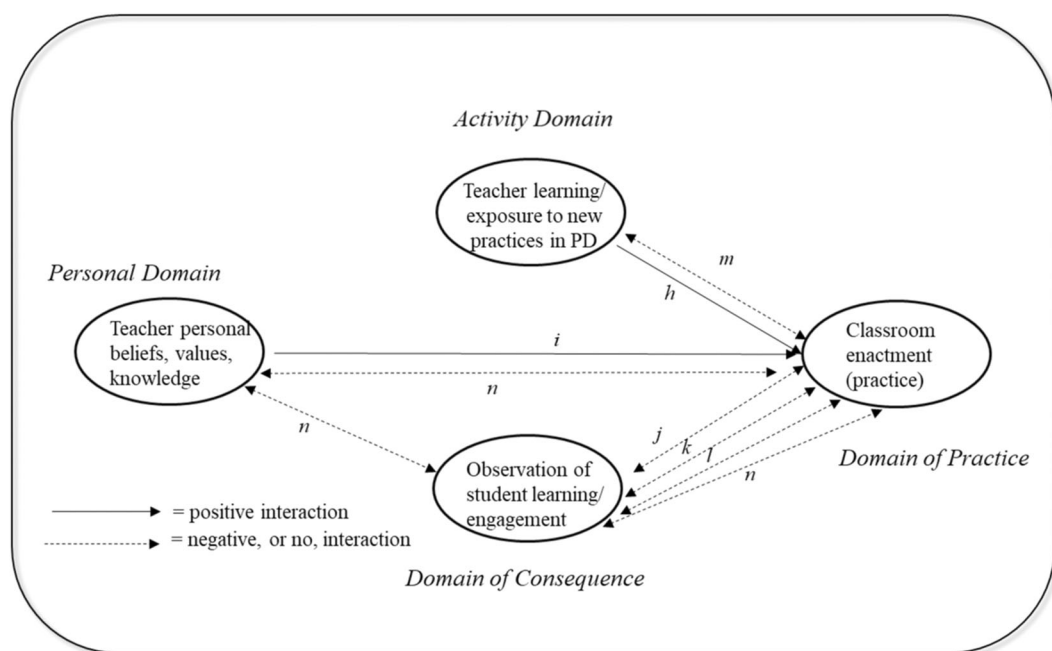


FIGURE 4 Operationalization of the interconnected model of professional growth among static and Initiating teachers in PD.

- b) Teachers preliminarily trust that students are capable of three-dimensional science learning, and begin to monitor students' initial response.
- c) Teachers notice students' sensemaking/productive struggle in relationship with new instructional practices.
- d) Teachers leverage student assets and lived experiences in their practice.
- e) Teachers connect students' sensemaking, productive struggle, and lived experiences to their instructional practices and beliefs.
- f) Teachers use this evidence of student learning to reflect on, increase, and adapt SLP instructional practices skillfully.
- g) Teachers' beliefs of student agentic learning, as well as their CK and PCK, are reinforced and deepened, solidifying changes to instructional practice.

For teachers at the lower end of the change continuum, an example sequence looked as follows (Figure 4):

- h) Teachers try out a PD strategy in their practice, although this is often mechanistic.
- i) They believe in knowledge transmission, that students need to learn facts, and/or that only traditional, canonical scientific ideas are valuable for science learning.
- j) Teachers primarily notice student excitement rather than student sensemaking.
- k) Teachers struggle to connect students' classroom learning to instructional practice.
- l) If/when teachers do notice student learning, they often do not know how to build this learning into practice to engage students in further productive struggle.
- m) They do not deepen or expand implementation of SLP pedagogies into beliefs.
- n) Because they generally do not connect student learning to instructional practice, teacher beliefs about science teaching and learning and reform practices remain static.

5 | DISCUSSION

Educators take up and incorporate new ideas and knowledge differently in PD, resulting in variation in teacher learning and implementation that has been documented both quantitatively (Banilower et al., 2018; Fischer et al., 2018; Granger et al., 2019) and qualitatively (Franke et al., 2001; Longhurst et al., 2017; Molle, 2021). Studies using iterative models such as the IMTPG have shown that some of the variation in teacher learning is due to recursive reflections and enactments as teachers encounter new ideas, try them out in their classrooms, interpret student responses, and slowly shift their beliefs and understandings (Clarke & Hollingsworth, 2002; Jacobs et al., 2010; Sherin, 2002). Yet, most previous studies of this nature rely on small samples of one to three teachers, and few study the specific context of science education. The question of how teachers internalize reform-based science instructional practices is of particular importance in urban elementary science education, where teachers need strong support to resist disincentives toward reform practices (Hayes & Trexler, 2016; Hayes et al., 2023; Lee & Luykx, 2005; NASEM, 2021).

In the present study, we first determined how teachers varied in their understanding of reform practices from SLP (the PD), implementation of reform practices, and degree of perceived change (RQ1) (Grossman et al., 1999; Longhurst et al., 2017), resulting in a continuum of teacher learning. We then applied Clarke and Hollingsworth's (2002) Interconnected Model of Teacher Professional Growth (IMTPG) model to understand the role of interactions between domains in shaping teachers' instructional change (RQ2; 2a) (Franke et al., 2001; Widjaja et al., 2017). Finally, we unpacked a central domain, the domain of consequence, (i.e., where teachers notice student ideas, engagement, affect, and learning), and how noticing within the domain of consequence drives learning in other domains (RQ2b) (Jacobs et al., 2010; Sherin, 2002). Our results are discussed below in relation to theory and the literature.

First, we found that after similar levels of participation in SLP PD, teachers nonetheless differed in their instructional change (RQ1). This further supports existing findings in PD studies (Knight-Bardsley & McNeill, 2016; Longhurst et al., 2017; Molle, 2021), although the current study takes a unique approach of delineating groups of teachers at different levels on a continuum of change. While some teachers remained committed to teacher-centered instruction (Static), or tried out SLP strategies mechanistically (Initiating), others actively experimented with strategies from the PD (Advancing) or skillfully adapted SLP pedagogical principles to their students' needs (Nuanced). Of note, our placement of teachers into change categories describes change along a continuum of teacher learning. They are not summative assessments of teaching skill, experience, or competence, but rather reflect the diversity and complexity of viewpoints provided by their richly varied responses that illustrate expected variations in teacher change after 9 months of participation in SLP.

We then analyzed interview data to understand teachers' perspectives on the processes and interactions between domains of teacher professional learning that could explain this variation (RQ2). We found the domain of consequence (e.g., teachers' perception of students' learning behaviors in the classroom), in interaction with other domains, to be central to the teacher change process. This study thus provides additional evidence in support of the pivotal role of observing student learning for teacher learning and instructional change (Hayes et al., 2019; Heller et al., 2012; Justi & van Driel, 2006; Lomas, 2018; Nielsen, 2012; Voogt et al., 2011; Widjaja et al., 2017; Witterholt et al., 2012).

We then engaged in an inductive coding process to understand how the domain of consequence functioned to support teacher learning from the PD, in interaction with other domains (RQ2b). This resulted in three themes, which form the bulk of our findings. Our findings for theme one, relating student learning to pedagogy, indicate that the teachers most likely to realize this connection were those who noticed, then interpreted student thinking and discourse, and responded with actions in-the-moment. In the noticing literature, teachers are said to have learned the practice of professional noticing when they no longer observe themselves, and shift their focus to students (Sherin & Han, 2004; Sherin, 2002). Static teachers who had difficulty changing their practice struggled to notice because they were focused on their own pedagogical habits of delivery, and discrete content delivery such as

teaching vocabulary. They attended minimally to students' emergent ideas during science activities (domain of consequence), and they did not connect those ideas with reform PD strategies (activity domain). The disconnect made it difficult for them to interpret and respond to students, the more challenging of the noticing skills (Jacobs et al., 2010). And so, in turn, they did not internalize change in their beliefs and pedagogical content knowledge (personal domain).

Initiating teachers were overly reliant on the mechanics of reform practices, and had difficulty allowing student ideas to inform their practice, perhaps resulting from lack of confidence with both content and pedagogy (personal domain) (Kang & Anderson, 2015). As a result, their change was slow. In contrast, Advancing and Nuanced teachers demonstrated the ability to adjust lessons to support students' discourse around emergent ideas (Chen et al., 2019). Advancing teachers recalled purposeful shifts in their practice, as they attended to and responded to student ideas. Their noticing skills (practice domain) began to evolve alongside use of reform practices (activity domain), and the teachers' in-the-moment responses helped shape classroom adaptation (practice domain) of strategies learned in the PD (activity domain) (van Es & Sherin, 2021).

Nuanced teachers attended to novel student ideas (domain of consequence) with complex, precise, and nimble responses, spotlighting in-the-moment connections between their instructional moves and students' sensemaking (practice domain). As they became more attentive to how students were reasoning about science phenomena, and carefully interpreted students' models and explanations, they generated more substantive, and topic-specific (Gess-Newsome, 2015) meaning-making with their lessons (e.g., Emily's use of the cloud-in-a-bottle activity). They also noticed when important sensemaking was *missing* in student models and discourse, and adjusted lesson content accordingly to improve pace and coherence, and enhance classroom focus on substantive science ideas (Luna & Sherin, 2017). Thus, teachers' ability to connect student learning (domain of consequence) to their more confident experimentation (practice domain) with new pedagogies learned in the PD (activity domain), ranged from unyielding at the Static level, to intentional, in-the-moment implementation at the Nuanced reach of the change spectrum. Noticing the students' response (domain of consequence), in turn, was accompanied by a shift in knowledge and beliefs (personal domain) toward more student-centered instruction.

In theme two, students' engagement and productive struggle, we found that teachers who attended more closely to struggle and sensemaking, rather than simply noticing students' affect were more likely to implement SLP pedagogies in skillful ways, such as asking students to rephrase an idea, asking probing questions, or revisiting a prior lesson. Static and Initiating teachers who struggled with change did not talk as much about students' ideas. They noticed and remarked primarily on students' expressions of enthusiasm, rather than on their struggles to figure out phenomena. While engagement is key to youngsters embracing science (Jacobs et al., 2010), affect alone is not evidence of learning. But Static teachers didn't attend to science sensemaking (domain of consequence), and, thus, were unlikely to adjust strategies or insert responsive scaffolds (practice domain) to support productive struggle.

Initiators began to notice student learning in addition to affect, but they, too, often lacked strategies to scaffold student sensemaking, perhaps owing to lack of confidence (Sandholtz & Ringstaff, 2014; Windschitl et al., 2012), or insufficient discipline-specific PCK (Suarez, 2020). For example, Initiating teachers could often launch students' conversation with a question or phenomenon, but may not have known how to facilitate discourse that was productive in developing their science ideas or that equitably included all students (Windschitl et al., 2012, 2018). Initiators also stopped short of describing overall classroom cultures that could support productive struggle. They were challenged by student uncertainty (Chen et al., 2019), and sometimes responded to instances of cognitive dissonance by simply providing correct answers. Thus, stuttering interactions between domains produced only nascent professional growth in the personal domain.

Advancing teachers talked about how learning emerged when their classrooms were places with a culture for discourse, allowing them to move toward better fluency incorporating SLP strategies that encouraged students to make sense of phenomena. Because Advancers started to notice how particular pedagogies (practice domain)



resulted in productive struggle on the part of students (domain of consequence), they were more likely to integrate equitable sensemaking discourse and three-dimensional practices into their science instruction skillfully.

In contrast, Nuanced teachers viewed productive struggle as a resource (Lee et al., 2019) that enhanced classroom learning. They shifted their instructional moves (practice domain) depending on the need, at times removing scaffolds to amplify productive struggle, while at other times, probing students' surface-level discourse and vocabulary to push them toward deeper understanding of disciplinary ideas. Their full attention to the conditions for student sensemaking allowed them to move from implementing routines (e.g. sentence stems), to constructing a culture for authentic, engaged, peer-to-peer discourse. Such adaptation occurred through iterative interactions among strategies from the PD (activity domain), classroom experimentation with those strategies (practice domain), and observation of productive struggle (domain of consequence), leading to further changes in beliefs about children's capacity to learn science (personal domain).

Finally, in theme three, student assets, Static teachers whose beliefs tended to position students as vessels to be filled (Eastwell, 2002; Yager, 2000), and learning as the accumulation of facts (NRC, 2012; National Academies of Sciences, Engineering, and Medicine, 2021), had difficulty noticing students' assets in the learning process, and thus had difficulty letting go of teacher-centered instruction. In attending to student ideas in the everyday language of elementary age children, it is often difficult to interpret in-the-moment what is and is not critical to the science phenomenon at-hand, thus reflection in the domain of consequence becomes important to moving student ideas forward (Patterson Williams et al., 2020; van Zee et al., 2005). But Static teachers rarely engaged students' lived experiences in their teaching (practice domain), essentially depriving themselves of opportunities to reflect on how students' varied ways of knowing could influence classroom learning (domain of consequence) (King et al., 2021). Such hesitancy also stifled use of student discourse strategies from the PD (activity domain), so that students had few chances to learn from one another's different stories or prior knowledge. This, in turn, precluded Static teachers from being able to internalize SLP instructional practices (e.g. Summary Tables; Windschitl et al., 2018).

Initiators sometimes tried to incorporate students' lived experience. However, even when they perceived nascent ideas as valid and relevant (domain of consequence), they had trouble building student thinking into their instructional practice (Russo-Tait, 2023). This lack of connection made it difficult for Initiating teachers' own beliefs to shift (personal domain). Thus, at the lower end of the change continuum, absence of noticing in the domain of consequence resulted in minimal impact on practice, and minimal change in teacher pedagogical knowledge (personal domain).

Teachers at the higher reach of the change continuum (Advancing and Nuanced) attended to students' lived experiences, and made in-the-moment decisions to elevate nascent ideas they perceived as noteworthy (i.e., what counted as science in the classroom; Alonzo & Elby et al., 2014; Miller et al., 2018). Russ and Luna (2013) remind us that connections between current learning, prior lessons, and the knowledge students bring to the classroom can support more substantive sensemaking. Advancing teachers' beliefs that student contributions were valuable (personal domain) motivated them to incorporate student ideas that shaped and influenced the course of lessons (practice domain). Nuanced teachers not only believed students had the ability to solve problems with their own strategies, but those strategies became the basis for instruction. The changes they described in student learning aligned with their perceptions of students' abilities, creating a positive feedback loop: the more agency accorded students assets, the more precisely teachers' in-the-moment responses came to depend on the prior knowledge students brought to school. This, in concert with enhanced uptake of content and pedagogical knowledge from the PD changed personal beliefs about the value of student-centered science instruction (personal domain).

This study contributes to a small but growing body of literature that attempts to explain why teachers vary in their response to professional learning (Evans, 2014; Longhurst et al., 2017; Molle, 2021), demonstrating the value of noticing in concert with domains of teacher learning. Several studies that apply professional noticing practice to professional development lend insight into changes that occur dynamically among classroom practice, student learning and personal beliefs (Franke et al., 2001; Sherin, 2002; Witterholt et al., 2012), and describe student learning as a mediator of interactions between the teachers' beliefs and classroom practice. Franke et al. (2001)

described teachers who engaged in generative change as those who made student thinking central to their practice, had deep knowledge of student thinking, and saw themselves as continually building on this knowledge. Franke and colleagues found that these characteristics, acting together, resulted in differentiation among teacher categories of implementation. Similarly, our results demonstrate that part of teacher learning in PD is dependent on the complexity and nuance of teachers' application of noticing skills. Attending, interpreting, and responding in-the-moment allowed teachers to connect their instructional practice to student learning, notice and facilitate student productive struggle, and elevate students' lived experience as an asset for science learning. This suggests that the practice of professional noticing—attending to the domain of consequence—provides a vehicle to more deeply engage with student sensemaking. Specifically, the findings presented here showcase how the skills associated with noticing result in teachers more skillfully and deeply adapting new instructional practices from PD to the classroom context, and, to the extent this is so, help teachers shift their knowledge and beliefs about students' science learning capacity.

In addition, the focus on noticing, when applied together with domains of teacher change, allows for understanding the iterative feedback loops that occur in professional learning. In the present study, all teachers tried out SLP strategies. Differentiation occurred as experimentation with PD strategies interacted with existing pedagogical knowledge, beliefs and routines. Implementation and understanding were further shaped by the ways teachers interpreted and responded to student learning and lived experience, and how teachers connected these with instructional moves derived from the PD. Noticing how students responded, in turn, influenced teacher beliefs about students' capacity to learn science. Even among teachers who more highly valued student assets and learning before the PD, practice and beliefs shifted iteratively the more they implemented what they learned in PD and skillfully attended to how new practices affected student learning.

5.1 | Practical implications

Professional noticing, when embedded within PD that considers teachers' own classroom contexts can be the catalyst that helps teachers internalize insights gained from deeply attending to and learning from their students (Sherin & Han, 2004). This study indicates a potential to focus on noticing in PD as one way to support increased teacher learning and uptake of new pedagogies. For example, noticing can be used to support a shift in beliefs from seeing science as a body of external knowledge to seeing science education as a space to cultivate student epistemic agency as they make sense of phenomena, engaging their prior knowledge and experiences (Barton & Tan, 2009; Russ & Luna, 2013; Stroupe, 2014). Professional development that is grounded in noticing theory and techniques (such as teacher-initiated videorecording) (Luna & Sherin, 2017) can assist science teachers to more rapidly shift away from attending to student behavior and affect and towards attending, interpreting, and responding to students' ways of learning (Luna & Sherin, 2017). Structuring PD to embrace the voices and agency of teachers as they build on their noticing skills (Knight-Bardsley & McNeill, 2016) can encourage more teachers to move away from traditional, teacher-directed instructional practice, and more fully support reform practices such as modeling and equitable sensemaking discourse (McNeill & Krajcik, 2012; Varelas et al., 2008).

This study supports long-standing evidence that PD needs to be of long enough duration to allow for learning new strategies, trying them out in practice, and reflecting on student learning in community with other teachers (Desimone, 2009; Furman Shaharabani & Tal, 2017; Garet et al., 2001; Roth et al., 2011). It also indicates the need for differentiation in PD. For example, classroom observations facilitated over time by peer coaches could support Static and Initiating teachers to anticipate student responses and identify instructional shifts that adapt to the diverse ways in which students understand science phenomena. These teachers would also benefit from mapping pedagogical strategies to students' responses. Finally, Static and Initiating teachers could use support in understanding how to leverage student lived experience. This likely requires reflective unpacking of beliefs about student capabilities simultaneously to observing the student learning and engagement made possible through

elevating the language and discourse of historically marginalized students (Kayumova & Dou, 2022). Advancing and Nuanced teachers would benefit from an ongoing science community of practice where the focus is building existing noticing skills to better support questioning strategies or students' productive struggle. PD providers can structure the professional development around analyzing student artifacts, teacher goal setting, and classroom observations (e.g., lesson study, classroom video, and self-reflection). Although classroom video recordings were not part of our PD design, video analysis affords the opportunity for teachers to observe and reflect on their in-the-moment interpretations and responses (Jacobs et al., 2010; Sherin et al., 2011). All of these opportunities can further assist teachers to attend to more of the quality instructional events and reform pedagogical practices that support equitable sensemaking and discourse.

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CONFLICT OF INTEREST STATEMENT

The authors have no conflicts of interest to declare.

DATA AVAILABILITY STATEMENT

Data from this project is not available under the terms of the IRB with our academic institution.

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REFERENCES

- Alonzo, A., & Elby, A. (2014). The nature of student thinking and its implications for the use of learning progressions to inform classroom instruction. *Proceedings of International Conference of the Learning Sciences, ICLS*, 2(1), 1037–1041.
- Arievitch, I. M., & Haenen, J. P. P. (2005). Connecting sociocultural theory and educational practice: Galperin's approach. *Educational Psychologist*, 40(3), 155–165. https://doi.org/10.1207/s15326985ep4003_2
- Bae, C. L., Hayes, K. N., O'Connor, D. M., Seitz, J. C., & Distefano, R. (2016). The diverse faces of teacher leadership. *Journal of School Leadership*, 26(6), 905–937. <https://doi.org/10.1177/105268461602600602>
- Bae, C. L., Mills, D. C., Zhang, F., Sealy, M., Cabrera, L., & Sea, M. (2021). A systematic review of science discourse in K–12 urban classrooms in the United States: Accounting for individual, collective, and contextual factors. *Review of educational research*, 91(6), 831–877. <https://doi.org/10.3102/00346543211042415>
- Banilower, E., Smith, P. S., Malzahn, K., Plumley, C., Gordon, E., & Hayes, M. (2018). *Report of the 2018 NSSME+.* Horizon Research, Inc.
- Barnhart, T., & van Es, E. (2015). Studying teacher noticing: Examining the relationship among pre-service science teachers' ability to attend, analyze and respond to student thinking. *Teaching and Teacher Education*, 45, 83–93.
- Barton, A. C., & Tan, E. (2009). Funds of knowledge and discourses and hybrid space. *Journal of Research in Science Teaching*, 46(1), 50–73. <https://doi.org/10.1002/tea.20269>
- Chen, Y.-C., Benus, M. J., & Hernandez, J. (2019). Managing uncertainty in scientific argumentation. *Science Education*, 103(5), 1235–1276. <https://doi.org/10.1002/sce.21527>
- Clarke, D., & Hollingsworth, H. (2002). Elaborating a model of teacher professional growth. *Teaching and Teacher Education*, 18(8), 947–967.
- Colley, C., & Windschitl, M. (2016). Rigor in elementary science students' discourse: The role of responsiveness and supportive conditions for talk. *Science Education*, 100(6), 1009–1038. <https://doi.org/10.1002/sce.21243>
- Darling-Hammond, L., & Richardson, N. (2009). Teacher learning: What matters?, *Educational leadership* (Vol. 66, p. 46). Association for Supervision and Curriculum Development.

- Davis, E. A., & Smithey, J. (2009). Beginning teachers moving toward effective elementary science teaching. *Science Education*, 93(4), 745–770. <https://doi.org/10.1002/sce.20311>
- Davis, E. A., & Palincsar, A. S. (2023). Engagement in high-leverage science teaching practices among novice elementary teachers. *Science Education*, 107(2), 291–332. <https://doi.org/10.1002/sce.21766>
- Desimone, L. M. (2009). Improving impact studies of teachers' professional development: Toward better conceptualizations and measures. *Educational Researcher*, 38(3), 181–199.
- Dolfing, R., Prins, G. T., Bulte, A. M. W., Pilot, A., & Vermunt, J. D. (2021). Strategies to support teachers' professional development regarding sense-making in context-based science curricula. *Science Education*, 105(1), 127–165. <https://doi.org/10.1002/sce.21603>
- Dorph, R., Shields, P., Tiffany-Morales, J., Hartry, A., & McCaffrey, T. (2011). *High hopes—few opportunities: The status of elementary science education in California*. The Center for the Future of Teaching and Learning at WestEd.
- van Driel, J. H., Meirink, J. A., van Veen, K., & Zwart, R. C. (2012). Current trends and missing links in studies on teacher professional development in science education: A review of design features and quality of research. *Studies in Science Education*, 48(2), 1 29–160.
- Eastwell, P. (2002). Social constructivism. *Science Education Review*, 1(3), 82–86.
- Edelson, D. C., Reiser, B. J., McNeill, K. L., Mohan, A., Novak, M., Mohan, L., Affolter, R., McGill, T. A. W., Buck Bracey, Z. E., Deutch Noll, J., Kowalski, S. M., Novak, D., Lo, A. S., Landel, C., Krumm, A., Penuel, W. R., Van Horne, K., González-Howard, M., & Suárez, E. (2021). Developing research-based instructional materials to support Large-Scale transformation of science teaching and learning: The approach of the OpenSciEd middle school program. *Journal of Science Teacher Education*, 32(7), 780–804. <https://doi.org/10.1080/1046560X.2021.1877457>
- Education Data Partnership. (2019). *Alameda. Ed Data*. <https://www.ed-data.org/county/Alameda>
- Enderle, P., Grooms, J., Sampson, V., Sengul, O., & Koulagna, Y. (2022). How the co-design, use, and refinement of an instructional model emphasizing argumentation relates to changes in teachers' beliefs and practices. *International Journal of Science Education*, 44(14), 1–27. <https://doi.org/10.1080/09500693.2022.2115324>
- Erickson, F. (2011). On noticing teacher noticing. In M. G. Sherin, V. R. Jacobs & R. A. Philipp, (Eds.), *Mathematics teacher noticing: Seeing through teachers' eyes* (pp. 97–116). Routledge.
- van Es, E. A., & Sherin, M. G. (2021). Expanding on prior conceptualizations of teacher noticing. *ZDM - Mathematics Education*, 53(1), 17–27. <https://doi.org/10.1007/s11858-020-01211-4>
- Evans, L. (2014). Leadership for professional development and learning: Enhancing our understanding of how teachers develop. *Cambridge Journal of Education*, 44(2), 179–198.
- Fernandez, C., Hochgreb-Haegele, T., Eloy, A., & Blikstein, P. (2023). Beyond “having fun” as evidence of learning: A longitudinal case study of a teacher's evolving conception of Hands-On science activities. *Journal of Science Education and Technology*, 32, 241–255. <https://doi.org/10.1007/s10956-022-10012-1>
- Finkelstein, C., Jaber, L. Z., & Dini, V. (2019). Do I feel threatened? No... I'm learning!"—affective and relational dynamics in science professional development. *Science Education*, 103(2), 338–361. <https://doi.org/10.1002/sce.21489>
- Fischer, C., Fishman, B., Dede, C., Eisenkraft, A., Frumin, K., Foster, B., Lawrenz, F., Levy, A. J., & McCoy, A. (2018). Investigating relationships between school context, teacher professional development, teaching practices, and student achievement in response to a nationwide science reform. *Teaching and Teacher Education*, 72, 107–121. <https://doi.org/10.1016/j.tate.2018.02.011>
- Franke, M. L., Carpenter, T. P., Levi, L., & Fennema, E. (2001). Capturing teachers' generative change: A follow-up study of professional development in mathematics. *American Educational Research Journal*, 38(3), 653–689. <https://doi.org/10.3102/00028312038003653>
- Furman Shaharabani, Y., & Tal, T. (2017). Teachers' practice a decade after an extensive professional development program in science education. *Research in Science Education (Australasian Science Education Research Association)*, 47(5), 1031–1053. <https://doi.org/10.1007/s11165-016-9539-5>
- Furtak, E. M. (2017). Confronting dilemmas posed by three-dimensional classroom assessment: Introduction to a virtual issue of science education. *Science Education*, 101, 854–867. <https://doi.org/10.1002/sce.21283>
- Garet, M. S., Porter, A. C., Desimone, L., Birman, B. F., & Yoon, K. S. (2001). What makes professional development effective? Results from a national sample of teachers. *American Educational Research Journal*, 38(4), 915–945.
- Gess-Newsome, J. (2015). A Model of teacher professional knowledge and skill including PCK. In A. Berry, P. J. Friedrichsen & J. Loughran, (Eds.), *Re-examining pedagogical content knowledge in science education* (pp. 28–42). Routledge.
- Goldsmith, L. T., Doerr, H. M., & Lewis, C. C. (2014). Mathematics teachers' learning: A conceptual framework and synthesis of research. *Journal of Mathematics Teacher Education*, 17(1), 5–36. <https://doi.org/10.1007/s10857-013-9245-4>
- Granger, E. M., Bevis, T. H., Southerland, S. A., Saka, Y., & Ke, F. (2019). Examining features of how professional development and enactment of educative curricula influences elementary science teacher learning. *Journal of Research in Science Teaching*, 56(3), 348–370. <https://doi.org/10.1002/tea.21480>

- Grossman, P. L., Smagorinsky, P., & Valencia, S. (1999). Appropriating tools for teaching English: A theoretical framework for research on learning to teach. *American Journal of Education*, 108(1), 1–29. <https://doi.org/10.1086/444230>
- Guskey, T. R. (2002). Professional development and teacher change. *Teachers and Teaching*, 8(3), 381–391.
- Hanley, P., Wilson, H., Holligan, B., & Elliott, L. (2020). Thinking, doing, talking science: The effect on attainment and attitudes of a professional development programme to provide cognitively challenging primary science lessons. *International Journal of Science Education*, 42(15), 2554–2573.
- Hayes, K. N., & Trexler, C. J. (2016). Testing predictors of instructional practice in elementary science education: the significant role of accountability. *Science Education*, 100(2), 266–289. <https://doi.org/10.1002/sce.21206>
- Hayes, K. N., Wheaton, M., & Tucker, D. (2019). Understanding teacher instructional change: the case of integrating NGSS and stewardship in professional development. *Environmental Education Research*, 25(1), 115–134. <https://doi.org/10.1080/13504622.2017.1396289>
- Hayes, K. N., Preminger, L., & Bae, C. L. (2023). Why does teacher learning vary in professional development? Accounting for organisational conditions. *Professional Development in Education*, 50(1), 108–128. <https://doi.org/10.1080/19415257.2023.2283433>
- Hayes, K. N., Bae, C. L., O'Connor, D., & Seitz, J. C. (2020). Beyond funding: How organizational resources support science professional learning. *American Journal of Education*, 126(3), 389–422. <https://doi.org/10.1086/708266>
- Heller, J. I., Daehler, K. R., Wong, N., Shinohara, M., & Miratrix, L. W. (2012). Differential effects of three professional development models on teacher knowledge and student achievement in elementary science. *Journal of Research in Science Teaching*, 49(3), 333–362. <https://doi.org/10.1002/tea.21004>
- Heredia, S. C. (2020). Exploring the role of coherence in science teachers' sensemaking of science-specific formative assessment in professional development. *Science Education*, 104(3), 581–604. <https://doi.org/10.1002/sce.21561>
- Hershberger, K., & Zembal-Saul, C. (2015). Methods and strategies: KLEWS to explanation-building in science. *Science and Children*, 52(6), 66–71. https://doi.org/10.2505/4/sc15_052_06_66
- Huberman, M., & Miles, M. B. (2002). *The qualitative researcher's companion*. Sage.
- Jacobs, V. R., Lamb, L. L. C., & Philipp, R. A. (2010). Professional noticing of children's mathematical thinking. *Journal for Research in Mathematics Education*, 41, 169–202.
- Justi, R., & van Driel, J. (2006). The use of the interconnected model of teacher professional growth for understanding the development of science teachers' knowledge on models and modelling. *Teaching and Teacher Education*, 22(4), 437–450.
- Kang, H., & Anderson, C. W. (2015). Supporting preservice science teachers' ability to attend and respond to student thinking by design: Responding to student thinking. *Science Education*, 99(5), 863–895. <https://doi.org/10.1002/sce.21182>
- Kayumova, S., & Dou, R. (2022). Equity and justice in science education: Toward a pluriverse of multiple identities and onto-epistemologies. *Science Education*, 106(5), 1097–1117. <https://doi.org/10.1002/sce.21750>
- Kennedy, M. M. (2016). How does professional development improve teaching? *Review of Educational Research*, 86(4), 945–980. <https://doi.org/10.3102/0034654315626800>
- King, N. S., Collier, Z., Johnson, B. G., Acosta, M., & Southwell, C. N. (2021). Determinants of black families' access to a community-based STEM program: A latent class analysis. *Science Education*, 105(6), 1100–1125. <https://doi.org/10.1002/sce.21669>
- Knight-Bardsley, A. M., & McNeill, K. L. (2016). Teachers' pedagogical design capacity for scientific argumentation. *Science Education*, 100(4), 645–672. <https://doi.org/10.1002/sce.21222>
- Korthagen, F. (2016). Inconvenient truths about teacher learning: Towards professional development 3.0. *Teachers and Teaching, Theory and Practice*, 23(4), 387–405. <https://doi.org/10.1080/13540602.2016.1211523>
- Lee, O., & Luykx, A. (2005). Dilemmas in scaling up innovations in elementary science instruction with nonmainstream students. *American Educational Research Journal*, 42(3), 411–438. <https://doi.org/10.3102/00028312042003411>
- Lee, O., Llosa, L., Grapin, S., Haas, A., & Goggins, M. (2019). Science and language integration with English learners: A conceptual framework guiding instructional materials development. *Science Education*, 103(2), 317–337. <https://doi.org/10.1002/sce.21498>
- Lehrer, R., & Schauble, L. (2012). Seeding evolutionary thinking by engaging children in modeling its foundations. *Science Education*, 96(4), 701–724. <https://doi.org/10.1002/sce.20475>
- Lemke, J. L. (2001). Articulating communities: Sociocultural perspectives on science education. *Journal of Research in Science Teaching*, 38(3), 296–316.
- Lewis, C., Perry, R., & Murata, A. (2006). How should research contribute to instructional improvement? The case of lesson study. *Educational Researcher*, 35(3), 3–14. <https://doi.org/10.3102/0013189X035003003>
- Lewis, E. B., Baker, D. R., & Holding, B. A. (2015). Science teaching reform through professional development: teachers' use of a scientific classroom discourse community model. *Science Education*, 99(5), 896–931. <https://doi.org/10.1002/sce.21170>

- Lomas, L. (2018). *Proposed structural refinements to the interconnected model of teacher professional growth*. Mathematics Education Research Group of Australasia.
- Longhurst, M. L., Jones, S. H., & Campbell, T. (2017). Factors influencing teacher appropriation of professional learning focused on the use of technology in science classrooms. *Teacher Development*, 21(3), 365–387. <https://doi.org/10.1080/13664530.2016.1273848>
- Loucks-Horsley, S., Stiles, K. E., Mundry, S., Love, N., & Hewson, P. W. (2010). *Designing professional development for teachers of science and mathematics*. Thousand Oaks.
- Luna, M., & Selmer, S. (2021). Examining the responding component of teacher noticing: A case of one teacher's pedagogical responses to students' thinking in classroom artifacts. *Journal of Teacher Education*, 72(5), 579–593. <https://doi.org/10.1177/00224871211015980>
- Luna, M. J., & Sherin, M. G. (2017). Using a video club design to promote teacher attention to students' ideas in science. *Teaching and Teacher Education*, 66, 282–294. <https://doi.org/10.1016/j.tate.2017.04.019>
- MacDonald, R., Miller, E., & Lord, S. (2016). Doing and talking science: Engaging ELs in the discourse of the science and engineering practices. In A. Oliveira & M. Weinburgh, (eds), *Science teacher preparation in content-based second language acquisition*. ASTE Series in Science Education. Springer. https://doi.org/10.1007/978-3-319-43516-9_10
- Maeng, J. L., Whitworth, B. A., Bell, R. L., & Sterling, D. R. (2020). The effect of professional development on elementary science teachers' understanding, confidence, and classroom implementation of reform-based science instruction. *Science Education*, 104(2), 326–353. <https://doi.org/10.1002/sce.21562>
- Manz, E. (2012). Understanding the codevelopment of modeling practice and ecological knowledge. *Science Education*, 96(6), 1071–1105. <https://doi.org/10.1002/sce.21030>
- Manz, E., & Suárez, E. (2018). Supporting teachers to negotiate uncertainty for science, students, and teaching. *Science Education*, 102(4), 771–795. <https://doi.org/10.1002/sce.21343>
- McNeill, K. L., & Krajcik, J. S. (2012). *Supporting grade 5-8 students in constructing explanations in science: the claim, evidence, and reasoning framework for talk and writing*. Pearson.
- McNeill, K. L., & Knight, A. M. (2013). Teachers' pedagogical content knowledge of scientific argumentation: the impact of professional development on K-12 teachers. *Science Education*, 97(6), 936–972. <https://doi.org/10.1002/sce.21081>
- Michaels, S., & O'Connor, C. (2012). *Talk science primer* - TERC. The Inquiry Project. https://inquiryproject.terc.edu/shared/pd/TalkScience_Primer.pdf
- Miller, E., Manz, E., Russ, R., Stroupe, D., & Berland, L. (2018). Addressing the epistemic elephant in the room: Epistemic agency and the next generation science standards. *Journal of Research in Science Teaching*, 55, 1053–1075. <https://doi.org/10.1002/tea.21459>
- Moje, E. B., Ciechanowski, K. M., Kramer, K., Ellis, L., Carrillo, R., & Collazo, T. (2004). Working toward third space in content area literacy: An examination of everyday funds of knowledge and discourse. *Reading Research Quarterly*, 39, 38–70.
- Molle, D. (2021). A close look at teacher learning: Why are teachers' journeys so different? *Teaching and Teacher Education*, 100, 103280. <https://doi.org/10.1016/j.tate.2021.103280>
- Morales-Doyle, D. (2019). There is no equity in a vacuum: On the importance of historical, political, and moral considerations in science education. *Cultural Studies of Science Education*, 14(2), 485–491. <https://doi.org/10.1007/s11422-019-09925-y>
- Nielsen, B. L. (2012). Science teachers' meaning-making when involved in a school-based professional development project. *Journal of Science Teacher Education*, 23(6), 621–649. <https://doi.org/10.1007/s10972-012-9300-5>
- Odden, T. O. B., & Russ, R. S. (2019). Defining sensemaking: bringing clarity to a fragmented theoretical construct. *Science Education*, 103(1), 187–205. <https://doi.org/10.1002/sce.21452>
- Opfer, V. D., & Pedder, D. (2011). Conceptualizing teacher professional learning. *Review of Educational Research*, 81(3), 376–407.
- Patterson Williams, A. D., Higgs, J. M., & Athanases, S. Z. (2020). Noticing for equity to sustain multilingual literacies. *Journal of Adolescent & Adult Literacy*, 63(4), 457–461. <https://doi.org/10.1002/jaal.1025>
- Penuel, W., Fishman, B. J., Gallagher, L. P., Korbak, C., & Lopez-Prado, B. (2009). Is alignment enough? Investigating the effects of state policies and professional development on science curriculum implementation. *Science Education*, 93(4), 656–677. <https://doi.org/10.1002/sce.20321>
- Robertson, A. D., Scherr, R. E., & Hammer, D. (2016). *Responsive teaching in science and mathematics*, Taylor & Francis Group.
- Roth, K. J., Garnier, H. E., Chen, C., Lemmens, M., Schwille, K., & Wickler, N. I. Z. (2011). Videobased lesson analysis: Effective science PD for teacher and student learning. *Journal of Research in Science Teaching*, 48(2), 117–148. <https://doi.org/10.1002/tea.20408>
- Russ, R. S., & Luna, M. J. (2013). Inferring teacher epistemological framing from local patterns in teacher noticing. *Journal of Research in Science Teaching*, 50(3), 284–314. <https://doi.org/10.1002/tea.21063>

- Russo-Tait, T. (2023). Science faculty conceptions of equity and their association to teaching practices. *Science Education*, 107(2), 427–458. <https://doi.org/10.1002/sce.21781>
- Sandholtz, J. H., & Ringstaff, C. (2014). Inspiring instructional change in elementary school science: The relationship between enhanced self-efficacy and teacher practices. *Journal of Science Teacher Education*, 25(6), 729–751. <https://doi.org/10.1007/s10972-014-9393-0>
- Sandholtz, J. H., Ringstaff, C., & Matlen, B. (2019). Coping with constraints: Longitudinal case studies of early elementary science instruction after professional development. *Journal of Educational Change*, 20(2), 221–248. <https://doi.org/10.1007/s10833-019-09338-2>
- Schipper, T., Goei, S. L., de Vries, S., & van Veen, K. (2017). Professional growth in adaptive teaching competence as a result of lesson study. *Teaching and Teacher Education*, 68, 289–303. <https://doi.org/10.1016/j.tate.2017.09.015>
- National Research Council. (2012). *A framework for K-12, Science education: Practices, crosscutting concepts, and core ideas*. National Academies Press.
- NGSS Lead States. (2013). *Next generation science standards: For states, by states*. The National Academies Press.
- Sherin, M. G. (2002). When teaching becomes learning. *Cognition and Instruction*, 20(2), 119–150. <https://www.jstor.org/stable/3233872>
- National Academies of Sciences, Engineering, and Medicine. (2021). *Science and engineering in preschool through elementary grades: The brilliance of children and the strengths of educators*. The National Academies Press. <https://doi.org/10.17226/26215>
- Sherin, M. G., & Han, S. Y. (2004). Teacher learning in the context of a video club. *Teaching and Teacher Education*, 20(2), 163–183. <https://doi.org/10.1016/j.tate.2003.08.001>
- Sherin, M. G., Russ, R. S., & Colestock, A. A. (2011). Accessing mathematics teachers' in-the-moment noticing: Seeing through teachers' eyes. In M. G. Sherin, V. R. Jacobs & R. A. Philipp, (Eds.), *Mathematics teacher noticing: Seeing through teachers' eyes* (pp. 79–94). Routledge.
- Shulman, L. S. (1986). Those who understand: Knowledge growth in teaching. *Journal of Education* (Boston, Mass.), 193(3), 1–11. <https://doi.org/10.1177/002205741319300302>
- Southerland, S. A., Metcalf, A., Schellinger, J., & Krishnan, H. (2023). *Exploring the External Domain: Describing the Role of Collaboration on Teacher Learning [Paper presentation]*. National Association for Research in Science Teaching Annual Meeting, Chicago, IL.
- Stolk, M. J., De Jong, O., Bulte, A. M. W., & Pilot, A. (2010). Exploring a framework for professional development in curriculum innovation: Empowering teachers for designing context-based chemistry education. *Research in Science Education* (Australasian Science Education Research Association), 41(3), 369–388. <https://doi.org/10.1007/s11165-010-9170-9>
- Stroupe, D. (2014). Examining classroom science practice communities: How teachers and students negotiate epistemic agency and learn science-as-practice. *Science Education*, 98(3), 487–516. <https://doi.org/10.1002/sce.21112>
- Suárez, E. (2020). "Estoy explorando science": Emergent bilingual students problematizing electrical phenomena through translanguaging. *Science Education*, 104(5), 791–826. <https://doi.org/10.1002/sce.21588>
- Tekkurmu-Kisa, M., Schunn, C., Stein, M. K., & Reynolds, B. (2017). Change in thinking demands for students across the phases of a science task: An exploratory study. *Research in Science Education* (Australasian Science Education Research Association), 49(3), 859–883. <https://doi.org/10.1007/s11165-017-9645-z>
- Upadhyay, B. R. (2006). Using students' lived experiences in an urban science classroom: An elementary school teacher's thinking. *Science Education*, 90(1), 94–110. <https://doi.org/10.1002/sce.20095>
- Varelas, M., Pappas, C. C., Kane, J. M., Arsenault, A., Hanks, J., & Cowan, B. M. (2008). Urban primary-grade children think and talk science: Curricular and instructional practices that nurture participation and argumentation. *Science Education*, 92(1), 65–95. <https://doi.org/10.1002/sce.20232>
- Voogt, J., Westbroek, H., Handelzalts, A., Walraven, A., McKenney, S., Pieters, J., & de Vries, B. (2011). Teacher learning in collaborative curriculum design. *Teaching and Teacher Education*, 27(8), 1235–1244.
- Wayne, A. J., Yoon, K. S., Zhu, P., Cronen, S., & Garet, M. S. (2008). Experimenting with teacher professional development: Motives and methods. *Educational Researcher*, 37(8), 469–479. <https://doi.org/10.3102/0013189X08327154>
- Wei, R. C., Darling-Hammond, L., Andree, A., Richardson, N., & Orphanos, S. (2009). *Professional learning in the learning profession: A status report on teacher development in the U.S and abroad: technical report*. National Staff Development Council.
- Widjaja, W., Vale, C., Groves, S., & Doig, B. (2017). Teachers' professional growth through engagement with lesson study. *Journal of Mathematics Teacher Education*, 20(4), 357–383.
- Wilson, S. M. (2013). Professional development for science teachers. *Science*, 340(6130), 310–313. <https://doi.org/10.1126/science.1230725>
- Windschitl, M., Thompson, J. J., & Braaten, M. L. (2018). *Ambitious science teaching*. Harvard Education Press.

- Windschitl, M., Thompson, J., Braaten, M., & Stroupe, D. (2012). Proposing a core set of instructional practices and tools for teachers of science. *Science Education*, 96(5), 878–903. <https://doi.org/10.1002/sce.21027>
- Windschitl, M. A., & Stroupe, D. (2017). The three-story challenge: Implications of the next generation science standards for teacher preparation. *Journal of Teacher Education*, 68(3), 251–261. <https://doi.org/10.1177/0022487117696278>
- Witterholt, M., Goedhart, M., Suhre, C., & van Streun, A. (2012). The interconnected model of professional growth as a means to assess the development of a mathematics teacher. *Teaching and Teacher Education*, 28(5), 661–674.
- Wongsopawiro, D. S., Zwart, R. C., & van Driel, J. H. (2017). Identifying pathways of teachers' PCK development. *Teachers and Teaching*, 23(2), 191–210.
- Yager, R. E. (2000). The constructivist learning model. *The Science Teacher (National Science Teachers Association)*, 67(1), 44–45.
- Yoon, K. S., Duncan, T., Lee, S. W.-Y., Scarloss, B., & Shapley, K. L. (2007). Reviewing the Evidence on How Teacher Professional Development Affects Student Achievement. Issues & Answers. REL 2007-No. 033. In *Regional Educational Laboratory Southwest*.
- van Zee, E. H., Hammer, D., Bell, M., Roy, P., & Peter, J. (2005). Learning and teaching science as inquiry: A case study of elementary school teachers' investigations of light. *Science Education*, 89(6), 1007–1042.
- Zwart, R. C., Wubbels, T., Bergen, T. C. M., & Bolhuis, S. (2007). Experienced teacher learning within the context of reciprocal peer coaching. *Teachers and Teaching*, 13(2), 165–187.

SUPPORTING INFORMATION

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