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Research paper

Desirable uncertainty in science teaching: Exploring teachers' perceptions and practice of using student scientific uncertainty as a pedagogical resource

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ABSTRACT

Science practice introduces inevitable uncertainties that are desirable for learning. Yet, navigating student scientific uncertainties can be a challenge for teachers. This qualitative study explored how teachers perceive and utilize uncertainty during science instruction. Analysis of interviews and classroom observations collected from 14 middle school teachers in the United States indicated limited awareness of uncertainty's use as a resource in science. Teachers perceived uncertainty as a way to induce curiosity and persist through struggle; however, they were quick to reduce students' scientific uncertainty throughout lessons. Findings suggest that teachers need support to understand how uncertainty navigation can benefit student learning.

1. Introduction

Recent decades have seen a global shift in science education towards authentic engagement in *science practice,* interrelated reasoning and actions used to develop scientific knowledge (Erduran & Dagher, 2014; Ford, 2015; Stroupe, 2015). Science practice entails inevitable uncertainties due to questioning, investigating, and critiquing multiple pathways toward solutions (Ford & Forman, 2015; Jordan et al., 2014; Meijers, 2000). Recognizing the ubiquity of uncertainty, current science education reform and research (Adams et al., 2018; NGSS Lead States, 2013; OECD, 2019) call for teachers to engage students in disciplinary practices with problematized phenomena and explore their uncertainties in order to improve comprehension and sense-making. Problematizing phenomena often begins with an initial source of uncertainty, and persistent uncertainties (Chowdhury et al., 2011) can increase through information-seeking processes, helping drive inquiry forward (Chen & Techawitthayachinda, 2021; Phillips et al., 2017; Watkins et al., 2017). While we acknowledge uncertainties are inherent to learning in general, we focus on the uncertainties specific to student engagement in scientific practices. Therefore, we define *scientific uncertainty* as students' psychological disposition accompanying confusion, wonder, curiosity, and perplexity about what and how existing knowledge can explain a problematized phenomenon during science learning. Scientific uncertainty can include *content uncertainties* (e.g., what do I not know; what knowledge do I need to know) as well as *epistemic uncertainties* (e.g., how do I come to know; how can I pursue knowledge; Chen & Qiao, 2020).

However, scientific uncertainties may not always be desirable in learning. Teachers' acknowledgement of student scientific uncertainty throughout science learning can support the construction of new knowledge through inquiry processes such as questioning, arguing claims, and sharing reasoning (Tiberghien et al., 2014). Alternatively, when uncertainty goes unrecognized or unacknowledged, the potential for productive struggle and knowledge development decreases. Given the inevitability and productive potential of uncertainty, teachers should understand and work with student uncertainties that occur during science practice, thereby leveraging student scientific uncertainty as a pedagogical resource. However, teachers often perceive uncertainty as a barrier to be avoided or resolved as quickly as possible, thus, navigating uncertainty can be a challenge (Bruner, 1986; Doyle & Carter, 1984; Lee et al., 2020). Teachers may provide students insufficient time to grapple with their uncertainties, persist through struggle, or generate and explore new questions, thereby limiting opportunities to make deeper connections and engage with authentic science practice (Chen & Techawitthayachinda, 2021; Manz & Suárez, 2018). Thus, there is a need to explore how science teachers currently perceive and utilize student scientific uncertainty. Such studies can inform the design of professional development and teacher education experiences that

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foster teachers' abilities to use uncertainty to support science learning.

In previous research, the values that science teachers espouse have been found to influence their pedagogical practices and how they enact instruction (Bryan & Atwater, 2002; Yerrick et al., 1997). Therefore, whether uncertainty becomes desirable in the science classroom likely depends on the relationship between a teacher's perceptual and enacted responses (Manz & Suárez, 2018). Nonetheless, few scholars to date have closely examined the relationship between teachers' perceptions and their instructional practices surrounding the use of student scientific uncertainty as a pedagogical resource (Manz & Suárez, 2018; see also sense-making science literature, Haverly et al., 2020; Schwarz et al., 2021). Thus, the purpose of the qualitative interpretive study presented here is to unpack teachers' perceptions of uncertainty related to science learning and identify pedagogical practices teachers use that elicit and facilitate opportunities for students to navigate their own scientific uncertainty and engage in productive struggle. Situated in the United States, the current study serves as a baseline of science teachers' perceptions and practice in order to design effective professional development that can foster teachers' purposeful use of student uncertainty as a pedagogical resource in science classrooms.

2. Theoretical perspectives: navigating desirable uncertainty as a pedagogical resource

Scholars across a wide range of disciplines agree that uncertainty can have both beneficial and detrimental effects on cognition, affect, and behavior (e.g., Anderson, 2003; Brashers, 2001; Tiedens & Linton, 2001; Wilson et al., 2005). Recognizing that not all uncertainty is desirable (Weaver, 1949), previous research has theorized distinctions between desirable and undesirable uncertainty in learning experiences (e.g., *good and bad uncertainty*; Beghetto, 2017, *productive and unproductive uncertainty*; Manz, 2018; McLaughlan et al., 2021, *desirable and undesirable difficulties*; Bjork & Bjork, 2011).

In this study, we define *desirable uncertainty* as student scientific uncertainties that a teacher recognizes, acknowledges, and supports as a pedagogical resource to prompt students to seek out new information, re-interpret previous (mis)understandings, and identify sources of struggle, thereby igniting curiosity, exploration, and discovery. Working with and persisting through uncertainties has the potential to enhance longer-term comprehension and transfer of knowledge (Bjork & Bjork, 2011), thus desirable uncertainty can motivate the process of learning. Conversely, *undesirable uncertainty* includes uncertainties that a teacher interprets and responds to as irrelevant to core concepts, sequenced in a manner that overloads students' cognitive capacity, or are deemed too complex for students' existing schema. These undesirable uncertainties can stem from teachers overlooking or not providing opportunities to acknowledge and navigate students' knowledge insufficiencies, misconceptions, ambiguities or anomalous results. This, in turn, can then lead to students' lack of productive engagement or unresolvable feelings of frustration.

Uncertainty is ubiquitous in science learning, and teachers' perceptions can trigger a shift between desirable or undesirable uncertainties. If teachers do not perceive uncertainty as a beneficial element in science teaching (i.e., *perceptual response)*, they will likely not plan to use student scientific uncertainty as a resource or recognize or facilitate student uncertainties (i.e., *enacted response*; Koşar, 2020). Moreover, teachers may not detect and identify sources of confusion as new information challenges previous understandings, unintentionally dismissing students' salient uncertainties.

2.1. Teacher's perceptual responses to uncertainty

As perceptions can drive enactment of teaching practice (Al Said et al., 2019; Braseth, 2022; Park et al., 2006; Urbina-Garcia, 2019), we suggest that the use of desirable uncertainty as a pedagogical resource may rely on the way teachers perceive uncertainty. Teachers can vary in their general orientation to uncertainty and the extent to which they tend to perceive uncertainty as an opportunity or a threat (Helsing, 2007), ultimately impacting the way they view potential outcomes. For example, perceiving uncertainty as a positive asset can help shift stressful and overwhelming feelings into opportunities to persist and welcome new possibilities (Campbell, 2007; Koşar, 2020).

As such, entangled orientations toward science may shape teachers' perceptions of uncertainty in the science classroom, thereby influencing their practice. Perceiving uncertainty as a threat in the science classroom can stem from teachers' beliefs about science as a discipline that emphasizes established knowledge (Donnelly, 1999; Sahin et al., 2023), or their beliefs about the role of teachers as the science authority in the classroom (Bae et al., 2022; Haverly et al., 2020). If teachers perceive uncertainty as a threat to instructional authority, they may be less likely to position themselves as science guides. Thus, they may be less willing and able to facilitate student choice and leverage student thinking about how to frame and investigate problematized phenomena (Manz, 2018; Schoerning et al., 2015).

2.2. Teachers' enacted responses to uncertainty

As a close relationship between uncertainty and knowledge development exists, uncertainty has been posited to follow multiple pathways through learning (Anderson, 2006; Kirch, 2010). For example, learning may elicit uncertainty or generate new uncertainties as a phenomenon is problematized, reduce uncertainty as knowledge is gained and sense made, or shift between topics as uncertainties are discovered and discussed (Reiser et al., 2021; Starrett et al., 2022). Therefore, the desirability of uncertainty that arises in science learning is dependent on teachers' pedagogical use of strategies to help students navigate their own uncertainties (Chen & Qiao, 2020; Manz & Suárez, 2018). Scholarly research on how individuals navigate uncertainty have theorized distinct strategies teachers can utilize, which we here call: raise, maintain, reduce, and postpone (Babrow et al., 1998; Brashers, 2001; Jordan & McDaniel, 2014).

Within the context of science learning, *raising uncertainty* entails purposefully inducing, generating, increasing, or calling attention to desirable uncertainty. Raising uncertainty can help students experiment with the possible, pose hypothetical questions, and increase curiosity (Beghetto, 2020; Williams & Brown, 2011). The process of raising uncertainty can evoke new questions related to the problematized phenomenon or extend ideas and curiosity toward a new pathway or application (McDaniel et al., 2003). *Maintaining uncertainty* involves acknowledging multiple possibilities while trying to filter and organize new information, prolonging discussions and adding new arguments to deepen understanding with new evidence and claims (Chen et al., 2019). Both processes of raising and maintaining uncertainty allow students to negotiate and co-construct understandings and meaning at various points in the learning process. Enabling these processes requires teachers to engage in iterative cycles of reflecting, planning, and in-the-moment decision making as they should be responsive to student questions and ideas, as well as preventing uncertainty from being prematurely reduced (Berland et al., 2020; Reiser et al., 2021).

Seeking out information to *reduce uncertainty* is another common strategy of uncertainty navigation (Brashers, 2001), and tactics for reducing uncertainty can foster desirable or undesirable uncertainty. Reducing uncertainty can foster engagement and enhance learning as new information is sought, however, if the goal is only to reduce the uncertainty quickly, knowledge gained may be surface-level (Brashers, 2001). To use reduction strategies to foster desirable uncertainty, teachers can scaffold information and guide students to solutions using familiar phenomena-based evidence without immediately providing answers themselves. Finally, *postponing uncertainty* is a strategy for acknowledging students' expressed uncertainties while maintaining instructional focus on the core phenomenon or practice at hand. This strategy can help lower students' frustration levels and prioritize information when questions and uncertainties are readdressed at a later time instead of being ignored entirely (Anderson, 2003; Brashers, 2001).

2.2.1. Using Storyline Principles to Chart Pathways of Uncertainty Navigation. Teachers' enactment of uncertainty navigation strategies may not necessarily occur in a linear fashion, as each lesson may raise new uncertainties while maintaining and reducing others (Davidson et al., 2020; Reiser et al., 2021). Therefore, our consideration of how teachers navigate uncertainty as a pedagogical resource is guided by principles of the *storyline model*, an approach to science instruction that involves connecting science learning experiences into a coherent sequence over time (Nordine et al., 2019; Reiser et al., 2021). Storyline principles are based on teachers' pedagogical actions that anchor phenomena in student sense-making. This entails being reflective and responsive to student ideas and uncertainties, while supporting students' experience of wrestling with uncertainties regarding steps to take during science investigations (Lowell et al., 2022; Reiser et al., 2021). Principles of the storyline model shift instruction away from teachers as presenter of information and mediator of correct answers (Reinholz & Shah, 2018). As such, teacher roles shift toward working with students to make decisions, co-construct investigations, and interpret inquiry outcomes as contributors to knowledge creation (Miller et al., 2018; Penuel et al., 2022).

Building on these recommendations, we contend that any sufficiently rich and rigorous storyline entails a temporal pathway of uncertainty navigation, whereby a teacher supports the generation and curtailment of uncertainty at opportune moments across a science lesson to support learning. Therefore, we apply storyline principles to our study of how teachers support and use desirable uncertainty in the science classroom, asserting that a pathway of uncertainty unfolds alongside the development of students' expanding knowledge construction of a problematized phenomenon. We conjecture that teachers' perceptual responses to uncertainty are likely to influence their ability to use student uncertainty to facilitate productive struggle during lesson enactment. Therefore, in this qualitative interpretive study, we aimed to explore teachers' perceptions toward uncertainty and their pedagogical practices of uncertainty navigation. The following research questions guided analyses.

> RQ 1: What perceptions do teachers express about the use of student scientific uncertainty as a pedagogical resource in the science classroom?
> RQ 2: How do teachers use uncertainty navigation strategies as part of their pedagogical practice in the science classroom?

3. Methods

3.1. Context and participants

Study participants include 14 teachers participating in the first year of a three-year project designed to support teachers in using student uncertainty throughout their science lessons. All teachers taught science between grades six-eight in one of five suburban districts within a metropolitan city in the southwestern United States. Teachers had varying science backgrounds and teaching experience (See Table 1). All teachers consented to participate in the Institutional Review Board (IRB) approved research, and all procedures were followed in accordance with the approved protocol.

Table 1
Participant information.

Pseudonym	Years teaching	Grade level(s) taught
Cameron	2	7th and 8th grade
Ash	4	7th and 8th grade
Jessie	5	6th grade
Ishana	5	7th and 8th grade
Emery	8	7th and 8th grade
Shaye	10	7th and 8th grade
Zion	15	6th grade
Charlie	16	7th and 8th grade
Indigo	16	7th and 8th grade
Marley	17	6th grade
Kyler	19	7th and 8th grade
Fin	20	7th and 8th grade
Esme	20+	6th, 7th and 8th grade
Addison	20+	7th and 8th grade

*Teachers ordered in number of years teaching experience.

3.2. Data sources

The two data sources were interviews and classroom observations for each of the 14 participants. The audio-recorded ~30-min semi-structured interviews focused on teachers' perceptions of uncertainty in science learning in order to address RQ1. The interview protocol contained 12 questions organized into three categories: (1) teaching and science background, (2) personal perceptions of uncertainty, and (3) pedagogical perceptions of uncertainty. Interviews were first transcribed in order to begin the analytic process of coding and comparing themes expressed throughout (DeCuir-Gunby et al., 2011).

Following the interviews, members of our research team conducted one classroom observation with each teacher throughout a science lesson (ranging from 30 to 55 min). Thirteen observations were audio-video recorded, supplemented with copious field notes. One teacher's observation was not recorded (Emery), due to not receiving permission to record, leaving analysis of their class observation dependent on observers' extensive field notes. Each observation focused on the teacher's instruction in order to address RQ2. Transforming the data to prepare for analysis, the first author created a content log for all the recordings (Jordan & Henderson, 1995), outlining the events of the science lesson, documenting how the teacher structured the lesson and how they initiated or responded to student uncertainties.

3.3. Data analysis

Our research team utilized a bottom-up approach to identify themes and create codes of teachers' uncertainty perceptions and practices derived from the data coupled with a top-down approach, using literature and current research to ground the findings in relation to the research questions (DeCuir-Gunby et al., 2011; Erickson, 2004; Thomas, 2006).

We first focused on analyzing the recorded interviews in order to understand how teachers initially perceived uncertainty (RQ1). The first author reviewed the data multiple times and organized responses into a spreadsheet based on interview questions to categorize the raw data (i.e., personal perceptions of uncertainty, perceptions of uncertainty in science classrooms, perceptions of strategies to identify/respond to student uncertainty), and made extensive memos to identify commonalities and differences in the teachers' perceptions of uncertainty and their reported responses to student uncertainty within the transcripted interviews (DeCuir-Gunby et al., 2011; Thomas, 2006). Utilizing a constant comparative method (Boeije, 2002) to look within and across each interview, our research team met to collectively review the data and illustrative examples, identifying themes and subthemes (Thomas, 2006; see Table 2).

Next, we focused on analyzing the classroom observations to identify how teachers utilized strategies to navigate and respond to uncertainty within their observed lesson (RQ2). Two researchers independently added detailed memos to identify and interpret specific moments in which a teacher supported uncertainty, the timing or sequencing of uncertainty, and moments where uncertainty was not addressed. To further support analysis for RQ2, our research team generated a rubric (See Table 3) to characterize how teachers organized their instruction and temporally facilitated a pathway for uncertainty. Drawing from our theoretical perspectives, we created categories for uncertainty storyline principles focusing on lesson structure and organization, as well as

Table 2
Overview of identified themes.

Theme a) student scientific uncertainty is desirable - only when bound by constraints	
Sub-themes	Examples from interview data
Primary use - engagement/spark initial curiosity	[Desirable uncertainty] is when students actually engage with it and ask questions, or show a little bit of confusion. I think the hardest part is when they're not engaged at all - Ishana
Valued the idea of persisting through struggle	It's fun to see kids struggling with a concept … It ignites a spark and just makes the kids love science, to explore it. - Addison
Theme b) limited awareness of potential sources of student scientific uncertainty	
Sub-themes	Examples from interview data
Uncertainty only stemmed from insufficient content knowledge	Well of course my inclination is to give them the answer, but you don't want to do that because just giving them the answer is not going to help them when they have to do the test - Esme
Oriented to uncertainty as a signal to give more information	[Student uncertainty] gives me anxiety and I want to jump in and rescue. It's very hard sometimes to see a kid struggle and not getting it, or even worse if they're on the wrong path. - Charlie

categories for specific strategies of uncertainty navigation including raising, maintaining, reducing, postponing. Through iterative rounds of negotiation, the rubric was organized into three levels of enactment using both theory and data.

The first author started with an independent pass, reviewing the recorded observations of three randomly selected teachers in order to analyze how they set up and supported opportunities for uncertainty navigation across the timespan of their lessons. The author added additional memos to the content log to identify potential gaps in the scoring rubric, reflect on themes and patterns, and add interpretations (Saldaña, 2013). They then met with two other authors to collaboratively operationalize and negotiate agreement of uncertainty navigation strategies and level of associated scores (i.e., 1, 2, or 3). Two authors then independently re-analyzed the rest of the observations based on the updated rubric before meeting to collaboratively negotiate (Smagorinsky, 2008) interpretations of teachers' instructional strategies and pedagogical practices and agree on scores of uncertainty navigation.

Throughout this process, our team used the negotiated and agreed-upon scores to identify events (i.e., chunks of instructional time), where teachers raised, maintained, reduced, or postponed uncertainty, creating temporal maps (Mercer, 2008). We organized temporal maps for each teacher, zooming out to examine how they structured their instruction at a macro-level temporal scale across episodes of the science lesson. New events were marked when teachers' instructional mode shifted (e.g., moving between a lecture to partner activities) or the teacher started to enact a navigational strategy based on their instruction, but it was not taken up and shifted to a different strategy. As an example of this shift in event coding, Jessie set up their class to debate student ideas, instructing students to critique and question other groups (e.g., scored as Maintain of 1). However, students remained quiet while the teacher then summarized and scaffolded student understanding without room for argumentation or debate (e.g., shifted to a score of Reduction of 2). Events with no evidence of the teacher navigating uncertainty were also noted. Time-stamps were added to represent the proportion of time each teacher spent facilitating the specific events; however this only included instructional time and did not account for time transitioning between activities; thus the strategies used did not all add up to 100% of the observed class lesson. We then color-coded each navigation strategy a different color, using shades of each color to represent the score level for each one according to the rubric (i.e., 0, 1, 2, or 3; See Fig. 1 in the results section).

4. Results

4.1. *Teachers' perceptions of student scientific uncertainty (RQ1)*

The first research question sought to understand teachers' perceptual responses to uncertainty expressed within their interviews. Overall, teachers' perceptions demonstrated a limited awareness of the potential use of student uncertainty. In general, teachers described uncertainty involved in science learning in a broad sense (e.g., uncertainties involved with not knowing all solutions, experimentation, and hypotheses). However, none of the teachers explicitly connected uncertainty to problematizing scientific phenomena or purposefully embedding or using uncertainty as a resource *throughout* science instruction. This limited awareness was evidenced within two themes. First, teachers perceived uncertainty as desirable when bound by constraints, i.e., (a) they restricted to inducing engagement and sparking initial curiosity; (b) they valued the idea of persisting through struggle. Second, teachers had limited awareness of potential sources of student uncertainty, i.e., (a) they recognized uncertainty only stemming from insufficient content knowledge; (b) they oriented to uncertainty as a signal to deliver information.

4.1.1. Uncertainty as Desirable when Bound by Constraints

The value of uncertainty expressed by teachers most often demonstrated a limited awareness of the potential pedagogical use of uncertainty, in that teachers focused on using uncertainty to elicit curiosity and struggle without connecting uncertainty to problematizing phenomena and driving student scientific storylines. Specifically, we noticed that the teachers valued uncertainty when bound within certain restraints including, (a) using uncertainty primarily to spark curiosity and initiate instruction, and (b) connecting the value of uncertainty with persisting through struggle, though without identifying what purpose the struggle serves during science learning.

Restricted to Inducing Engagement and Sparking Initial Curiosity (a). The majority of the teachers narrowed their perception of the desirability of uncertainty to students' engagement and wonderment, specifically at the beginning of a lesson. However, while wonder and curiosity may be associated with uncertainty, those constructs are not synonymous. Regardless, eliciting initial uncertainty was perceived as a tool to spark curiosity toward a new topic, exemplified in the following excerpt from Ash's interview.

> Desirable uncertainty would basically be at the beginning of the learning process. I'm introducing them to a new concept; I'm introducing them to something … they will be learning about, and it's engaging them in a new subject. Like, 'have you ever thought about how this thing occurs, or how chemicals bond to one another, or how everything's made up?' So these kinds of driving questions to get them to think, 'well, no, I haven't.' You know, to be like, 'okay, well we're going to learn about that today'. So the desirable uncertainty is the teaser almost, like, 'here's what we're going to be getting into.'

In this example, Ash connects desirable uncertainty with eliciting curiosity as part of engaging students in the learning process, specifically by using "driving questions" as a way to foster interest in the upcoming lesson. They express their perception that uncertainty is beneficial when constricted to the teaser or introduction of a new subject, perceiving it as a catalyst into a traditional lesson (i.e., "we're going to learn about that today"). This perception of uncertainty's use only to elicit initial

Table 3
Classroom observation rubric.

Codes to analyze how teachers organized their lesson structure and classroom instruction during observed lesson				
Enactment	Levels			
Uncertainty Storyline Principles	0	1	2	3
Reiser et al. (2021)	There is no lesson plan or pathway observed	Teacher enacted a lesson involving mostly (≥75% of class time) lectures and/or direct instruction with little time built in for student discovery or exploration. Knowledge building came primarily from teacher direction (e.g., lectures, PowerPoints, videos, teacher-created or -directed content)	Teacher organized their lesson integrating prior knowledge and provided a few opportunities for students to construct their own understanding and interpretations of the content. Teacher did not dig deeper into the content to identify student uncertainties or use student questions consistently	Teacher positioned students as co-authors in knowledge building by organizing their lesson trajectory to help students create learning goals, integrate prior knowledge and practices, explore uncertainties, and interpret, argue, and/or evaluate their own understanding. Students created questions to guide the learning trajectory
Codes to analyze how teachers facilitated and used student scientific uncertainty navigation strategies				
Enactment	Levels			
Raising	0	1	2	3
(Beghetto, 2020; Chen et al., 2019; Jordan, 2015)	This was not observed	Teacher problematized a phenomena only in the beginning of a topic or to elicit interest and foster engagement with the topic (surface level/shallow problematization), or raised initial uncertainty as an assessment tactic to gauge prior knowledge and awareness of topic. Teacher did not provide opportunity to dig into it for further exploration or to address uncertainties that were (or could be) raised	Teacher guided students through problematized phenomenon, providing time and opportunity for exploration of the same or continued topic; purpose is to practice higher level thinking and problem-solving skills; Used either everyday or investigative phenomenon to uncover or bring to light student misconceptions; Presented a new idea or information to generate further consideration of a phenomenon (insufficiency) or provide an experience to expose students to new information needed to raise uncertainty about a topic	Teacher invited students to extend the phenomenon in a new way (e.g., problematize, ask questions, generate wonderings, hypotheses or "what ifs"); Extended the topic in a new path or application by problematizing content (e.g., pose a question or a hypothetical scenario, offer an alternative pathway or interpretation, introduced errors, misconceptions, or ambiguities, add alternative justifiable interpretation or argument) and scaffolded student interactions; purpose is to increase higher level thinking and problem-solving skills; Used everyday and investigative phenomenon
Maintaining				
(Babrow et al., 1998; Chen et al., 2019; Michaels & O'Connor, 2015)	This was not observed	Teacher invited students to ask new questions, make inferences or predictions, identify new information, but did not provide space/time/scaffolding to develop the ideas or critique other arguments; asked students to work in groups to discuss ideas but did not provide additional structure that would lead to argumentation (e.g., debate or critique ideas)	Teacher compared conflicting ideas either from literature or student ideas without additional time to develop new arguments; Asked students to share reasoning and ideas (including doubt) without evaluating responses or critiquing arguments; acknowledged (verbally or nonverbally) that struggle is important and it is beneficial to work through challenges; Expressed value in thought process; Encouraged students to reflect on their work, persist through their struggle, and resist giving up	Teacher challenged students to clarify and critique arguments/claims made and strategically compared conflicting claims to stimulate alternative ideas; Rephrased questions or prompts to facilitate students' deeper exploration of ideas; Provided adequate wait time for reflection and surfacing of uncertainties or, when confronted with students' expressions of struggle, to allow students' thoughts to formulate and create ideas, even when incorrect; asked clarifying or open-ended questions to prompt students to focus on their thinking, clarify misconceptions, and identify the source of their struggle
Reducing				
(Babrow & Matthias, 2009; Brashers, 2001; Jordan, 2015)	This was not observed	Teacher gave answers promptly at the first sign of struggle, confirmed or simply validated answers or choices quickly - did not give details of why/how - provided answer key immediately; Asked students to summarize or recap given information or readdress previous ideas to correct misconceptions after learning content	Teacher asked students to discuss questions or uncertainties in groups and/or provided an answer key or resources if they got stuck. If the teacher immediately provided an answer, they explained the concept or reasoning. Teacher rephrased a question or prompt in order to get students to the correct answer; Teacher driven discussion with focus on correct answer; Contributed an idea that was needed for students to fix a misconception or have sufficient information to address a question or problematized phenomenon	Teacher invited students to seek out information needed, guided students to correct answers without telling them; Used familiar phenomena-based evidence or examples to explain target concepts; Guided students to conduct reasoning, inquiry through direct observation, and/or research using multiple resources; Centered students' ideas in extended discourse (student ideas drive conversation); Invited students to open up the possibility for new inquiry, wonderings, uncertainties
Postponing				
(Anderson, 2003; Brashers, 2001; Jordan, 2015)	This was not observed	Teacher did not address student questions or uncertainties, walked away from students or groups that were verbally not understanding the content	Teacher asked students to hold onto their predictions, questions or uncertainties, but did not re-address them later (within observed lesson); Conveyed that there is not currently sufficient time to address the issue	Teacher re-addressed students' prior uncertainties and questions that were initiated throughout the class

Participant	Time of observation	Temporal Map of Classroom Observations										
Cameron	48 min	NONE 00:9:10	Re (1) 9:10-14:35	R^ (1) 14:35-17:50	Re (2) 17:50-27:30	Re (1) 27:40-31:30	Re (1) 31:30-33:40	Re (1) 34:00-44:12				
Ash	40 min	NONE 00:00-7:40	M (1) 7:40 - 10:40	Re (1) 10:55-16:22	Re (2) 00:00-9:15	NONE 00:00-5:00	M (1) 2:48-3:10	NONE 5:45-11:00				
Jessie	52 min	R^ (1) 1:20 - 3:00	Re (2) 3:00 - 6:00	M (2) 9:05 - 23	M (1) 1:50 - 3:00	Re (1) 4:30 - 13:00	R^ (1) 14:30:19:25	Re (2) 19:25-20:00	Re (1) 21:12-27:25	Re (2) 4:40-7:55		
Ishana	46 min	NONE 00:8:40	Re (2) 8:40-25:40	Re (2) 25:40-31:50	R^ (1) 31:50-33:20	M (2) 00:00-12:30						
Shaye	54 min	R^ (1) 00:00-6:53	NONE 6:53-10:15	Re (1) 10:15-17:20	Re (2) 17:50-27:20	M (1) 27:25-28:20	NONE 28:20-30:00	Re (1) 30:00-54:00				
Zion	46 min	NONE 00:00-3:41	Re (1) 0:50-2:30	R^ (2) 3:05-9:37	Re (2) 11:00-14:50	M (2) 15:40-32:00	R^ (3) 12:25-17:40	Re (1) 18:40-20:00				
Charlie	45 min	NONE 1:24-2:30	R^ (2) 2:33-4:30	Re (1) 4:30-9:33	Re (1) 9:35-11:53	NONE 12:43-16:12	Re (1) 16:12-28:00	Re (1) 00:00-5:00	Re (2) 5:00-14:20	Re (2) 14:30-17:15		
Indigo	30 min	R^ (1) 00:00-00:45	Re (1) 3:10-10:55	Re (2) 00:00-12:45	Re (2) 00:00-6:50							
Marley	34 min	NONE 00:00-2:44	Re (1) 2:44-5:00	Re (1) 5:25-9:20	NONE 9:20-15:00	Re (2) 15:00-32:00	NONE 32:00-33:26					
Kyler	40 min	NONE 00:00-5:48	NONE 00:00-2:50	Re (1) 2:20-5:13	M (1) 5:13-7:10	Re (1) 7:10-11:12	M (1) 00:00-01:30	M (1) 1:30-2:45	Re (1) 2:45-9:15	NONE 1:43-9:06		
Fin	52 min	NONE 0:00 - 6:20	R^ (1) 6:20 - 8:55	M(2) 8:55-13:40	Re (2) 13:40-17:10	M (2) 17:10-22:19	Re (2) 00:55-6:40	Re (2) 7:10-14:40	M (1) 14:42-17:38	Re (2) 20:00-23:23	R^ (1) 23:23-24:25	Re (2) 24:25-29:43
Esme	55 min	NONE :00-15:00	NONE 15:23-20:28	Re (1) :00 - 7:50	Re (2) :00-8:28	Re (1) 26:36-34:00						
Addison	57 min	M (2) 00:00-6:00	NONE 6:00-12:15	Re (2) 12:45-18:50	Re (1) 18:50-25:30	M (2) 25:30-33:28	Re (2) 5:15-17:00	Re (1) 18:15-22:00				

KEY - color and number codes

Uncertainty Navigation Strategy	*Coded depth of each strategy*		
Raising - R^	1	2	3
Maintaining - M	1	2	3
Reducing - Re	1	2	3

Note. Events of no opportunities for uncertainty navigation are shaded as gray.

Fig. 1. Temporal maps of observed fractured uncertainty navigation pathways

curiosity was a common value expressed by most of the teachers. For example, Emery stated,

> Desirable uncertainty, I think, is basically another word for *wonder*, the idea of like, you don't know, but you want to, and you're not afraid to find out … It's something you're like, 'wow that's really cool, I want to know the answer to that, I have no idea how that works'

Both of these excerpts demonstrate that the teachers acknowledged a value that uncertainty has in science learning. However, their perceptions constrained the use of uncertainty to a teaching strategy to engage learners only when introducing new ideas. The expressed perceptions did not stretch to include using uncertainty to wrestle with problematized phenomena and initiate or engage in scientific practice (e.g., argue, question, critique ideas).

Furthermore, just as teachers perceived uncertainty as desirable when *raised* at the beginning of a lesson, many of the teachers perceived uncertainty as being undesirable when it was not *reduced* at the end of a lesson. Ten out of the 14 teachers expressed the use of sequencing (e.g., initiate at the beginning, reduce at end) as a way to differentiate desirable and undesirable uncertainties, expressing that uncertainty was undesirable when students still had uncertainties at the end of lessons. For example, Zion said, "… after we've done all our experiments, I don't want to finish the unit and have kids still uncertain", and Cameron explained, "it's not desirable for them to *not* know the answer at the end [of a lesson]".

Valued the Idea of Persisting Through Struggle (b). Twelve teachers connected desirable uncertainty with the importance of struggle within science practice. Specifically, teachers expressed a benefit of uncertainty as giving rise to opportunities for students to practice resilience or persistence needed to "deepen their understanding" (Zion) or "because it makes them grow" (Indigo). The connection between struggle and engagement in science learning tasks was a common value expressed by the teachers, yet they did not follow through with expressing *how* that struggle could play out productively (e.g., in a storyline, through inquiry). For example, when describing the importance of students struggling through learning new concepts, Cameron expressed,

> Sometimes I want them to struggle with a concept that's new … have the kids think and brainstorm and be uncertain and do exploration and try to figure it out … they remember that struggle, and then they're really proud of themselves when they figure it out.

In this example, Cameron did talk about strategies used in science inquiry (i.e., brainstorming, exploring), but then kept the response more generic without saying exactly how students would struggle through brainstorming and "doing exploration". Furthermore, they used the phrase "figure it out" several times when discussing their perceptions of students struggling with uncertainty, putting the main focus on students getting to the correct answer.

While acknowledging the benefits of struggle, some teachers explicitly acknowledged the pedagogical challenge of avoiding the urge to step in too quickly to buttress students through their struggle as a way to avoid frustration, discouragement, and withdrawal. For instance, Ishana stated, "It's hard to let them struggle with [uncertainty] … But I really need to try to let them struggle with it for a little bit … I think it's important to try to get comfortable with the uncomfortability". Ishana thus acknowledged the benefit of grappling with uncertainty, while realizing they, or their students, may not be comfortable persisting through the struggle. Ishana described the uncomfortable feeling that can accompany uncertainty and struggle while expressing the challenge of knowing when to step in to avoid potential negative emotions and undesirable uncertainty elicited by prolonged frustration. This need to balance support was echoed by Charlie, stating, "It's that point of how much do you give [students] so they stay engaged and don't shut down because it's too hard". Here, Charlie acknowledged the fine line of pushing students to persist without shutting down due to difficulty or being overwhelmed.

4.1.2. Teachers Had Limited Awareness of Potential Sources of Uncertainty.

The second main theme was that teachers' perceptual responses were largely limited in terms of awareness of possible sources of student uncertainty. This, in turn, constrained teachers' ability to perceive diverse strategies for navigating uncertainty and to recognize desirable uncertainty as a pedagogical resource. Specifically, analysis indicated that (a) the teachers perceived students' uncertainty as stemming from insufficiency of knowledge needed to understand new science concepts, and due to this perception, (b) the teachers largely oriented to student uncertainty as a signal of when the teacher should step in to reduce any residual uncertainties by delivering answers or additional information.

Recognized Uncertainty only Stemming from Insufficient Content Knowledge (a). The teachers largely oriented to student uncertainty concerning knowledge of content (e.g., prior experience with the science phenomenon), in contrast to uncertainty about epistemic issues (e.g., framing problems, how to interpret data, dealing with alternative ideas or arguments). When asked how they identify the source of student uncertainty, teachers often described their perceptual processes in terms of assessing knowledge deficiencies using tools such as tests or exit tickets. They used phrases like "understanding the concept" and the ability to "answer questions", limiting their consideration of student uncertainties to content knowledge deficiencies. For example, Kyler described,

> I do [checks for understanding] most of the time, so I get to know, he's got the concept, she didn't get the concept, or she got the concept, and so I get to know, yes, there is uncertainty, so we need to do something about those students'.

After describing types of informal assessments to check for students' content knowledge, Kyler immediately connected not "get [ting] the concept" with students having uncertainty that needs to be corrected (i.e., "we need to do something"). This perception was echoed by ten other teachers, expressing the importance of "concepts", and understanding the information given. We interpreted Kyler's interview excerpt above, and similar responses, as further indicating teachers' limited awareness of different possibilities to help students navigate uncertainty and for considering ways of using uncertainty as a resource to guide students to engage in science practices to address their own uncertainties.

In addition to recognizing only a limited type (i.e., content uncertainty) and source of uncertainty (i.e., knowledge insufficiency), Kyler's interview excerpt, and others like it, exemplifies how teachers did not distinguish students' experience of uncertainty from students answering a question incorrectly or expressing an incorrect idea. While students' incorrect responses *can* be indicative of uncertainty, Kyler's strategy of checking for understanding was used to identify students who do not know the correct solutions, not to identify students' uncertainty.

Oriented to Uncertainty as a Signal to Deliver Information (b). As teachers focused on content uncertainty stemming from insufficient knowledge, they perceived indications of students struggling with uncertainty as a signal to eliminate uncertainty by giving students more information. Teachers used phrases like the "wrong way" vs. "right way", "different direction", focusing on getting correct answers on tests and assignments, and eliminating any residual uncertainties. Such responses conveyed teachers' perceptions of uncertainty as a problem of knowledge insufficiency that needs to be fixed through information seeking strategies or, more often, through information being provided by the teacher directly. This contrasts with epistemic uncertainties of *how* students understand a phenomenon or come to understand information. Adding to the limited awareness of the use of uncertainty, teachers expressed a need to step in to quickly decrease or eliminate struggle or uncertainties. Esme, for instance, described a hypothetical scenario in which they respond to a student struggling,

> 'Now I want you [the student] to try one and I'll watch you do it.' And if they start to go wrong, then I'll go, 'nuh uh uh'. And they'll say, 'oh wait hold on, no I'm supposed to do this', and I'll be like 'yeah' … Sometimes if I see them struggling I'll get a piece of material that I think would work better.

In this excerpt, Esme is using students' struggle as a signal of when they should give more information. They described how they would provide support by telling students when they are incorrect, but then went on to say they find new resources to use as a way to relieve the struggle. In this hypothetical scenario, Esme did not immediately jump to providing additional content knowledge but did step in as soon as they noticed a student was "wrong". This eliminates opportunities to wrestle with understanding or reach a conclusion via students' own pathway. Esme expressed a need to deliver knowledge or provide students with content knowledge in order to reach a valid conclusion. This perspective was common throughout the interviews as teachers discussed addressing student uncertainties, continuing to put emphasis on a deficiency of student content knowledge and less on grappling with epistemic uncertainty to enhance sense-making and creative problem-solving skills.

4.2. Enacting instruction: teachers' difficulty eliciting and facilitating uncertainty (RQ2)

The second research question aimed to explore how teachers utilized uncertainty navigation strategies as part of their pedagogical practice when enacting science instruction. Overall, analyses of instruction during the observed lessons indicate that teachers relied heavily on teacher-directed and teacher-created knowledge in the structure of their lessons. Rather than facilitating student-constructed storylines (Haverly et al., 2020), the teachers focused on delivering information through lectures and direct instruction versus inviting students' questions or uncertainties to drive the lessons (e.g., using uncertainty storyline principles) as evidenced by the preponderance of lessons assigned the lowest storyline score (1 out of 3; See Table 4 for scores and Table 3 for storyline rubric).

As shown in Table 4 above, 11 of the teachers' lesson enactments were scored with a 1. These low scores indicate that those 11 teachers used mostly (e.g., more than 70% of the observed class period) direct instruction with lectures, and heavily directed knowledge construction opportunities. In these instances, students acted as passive receivers of knowledge (e.g., taking notes and filling in their guided worksheets) instead of co-creators.

These lessons, even when incorporating labs or experiments, involved heavily structured directions and procedures (e.g., describing how to move and use the materials, explaining the variables and how to create and label their graphs), thus eliminating any chance for error and opportunities for struggle. Furthermore, the majority of the teachers used IRE (initiate-respond-evaluate) style questioning in their lectures (e.g., close-ended questions that typically require a single-word student response which is quickly evaluated by the teacher; Schwarz et al., 2021). This practice limited opportunities to raise uncertainties and focused more on reducing them by quickly answering and providing information to move on.

Only three teachers' observed lessons, Zion, Jessie, and Emery, were given a mid-level score of 2 for uncertainty storyline principles (See Table 3). These teachers structured their lessons in a way that invited students to explain and argue their own understanding, provided opportunities for students to construct their own interpretations of the science phenomenon under study (e.g., moon phases, resource consumption, energy transfer) and used student-created questions to guide discussions. Nonetheless, all three of these teachers ended up taking control of the explanations and connections within the learning content, putting more responsibility on the teachers rather than inviting students to take ownership of their learning and explore their own ideas, indicating teacher-constructed storylines. In our storyline coding scheme, the top score of 3, was reserved for lessons in which teachers positioned students as co-creators and invited them to create *and* follow their own learning trajectories, explore their uncertainties, and evaluate their own understandings.

In summary, due in part to the lesson structures that were observed,

Table 4
Lesson structure overview for each classroom observation.

Pseudonym	Observed lesson/unit	Lesson structure in chronological time	Storyline score[a]
Cameron	Earth's systems	Direct instruction (PowerPoint lecture); watched video with worksheet; teacher directed answers to worksheet; teacher demonstration	1
Ash	Atoms and molecules	Administered a timed reading quiz; direct instruction (PowerPoint lecture) with guided notes	1
Jessie	Resource consumption	Small-group activity researching answers to student-generated questions; each group presented; watched video on scale vs. proportion; students were asked to construct arguments about phenomena	2
Ishana	Energy transfer	Direct instruction (PowerPoint lecture) with guided worksheet; small-group work to create a mini Rube Goldberg machine	1
Emery	Energy types and transfer	Small-group work to build and test a rollercoaster; teacher walked around to guide as needed	2
Shaye	Sources of energy	Direct instruction (video and PowerPoint lecture) while students took notes; small-group work to fill out worksheet	1
Zion	Moon phases	Administered a timed math test; whole group discussion and physical activity to model moon phases; small-group work to create definition booklets; presented new phenomena	2
Charlie	Digestive unit	Small-group lab; direct instruction (PowerPoint lecture) with guided worksheet; small-group activity to create definitions of vocabulary terms	1
Indigo	Crime scene investigations	Small-group lab; teacher directed instructions with structured guide provided	1
Marley	Phases of matter	Direct instruction (PowerPoint lecture) with guided worksheet; teacher read answers to whole class	1
Kyler	Climate change	Direct instruction (article dissemination) with individual note taking	1
Fin	Energy transfer	Direct instruction (PowerPoint lecture) with whole group discussions and hands on modeling	1
Esme	Matter	Direct instruction (lecture) with guided worksheet; read answers to whole class	1
Addison	Solar energy and energy sources	Direct instruction (PowerPoint lecture) while students took notes; small-group sorting activity; teacher read answers to whole class	1

[a] *Note*. Storyline scores represented in Fig. 1. Score of 1 indicates the lesson involved mostly lectures with little time built in for student discovery and exploration. Knowledge construction came primarily from the teacher. Score of 2 indicates teachers organized their lesson with few opportunities for students to construct their own knowledge and understanding but still guided the direction of the learning.

analyses of teachers' instruction yielded three main themes: (a) the teacher-constructed storylines led to fractured uncertainty navigation pathways, (b) teachers utilized surface-level reduction strategies most commonly throughout their instruction, and (c) teachers missed opportunities to facilitate and foster students' navigation strategies and engagement in productive struggle. Each of these themes is discussed in turn below.

4.2.1. Fractured uncertainty navigation pathways

Ultimately, across all 14 observed lessons, teacher-constructed storylines limited opportunities for students to experience desirable uncertainty throughout their learning experience. This led to *fractured uncertainty navigation pathways* (i.e., creating minimal opportunities for students to give voice to their uncertainty, providing no explicit opportunities for students to reflect and act on their scientific uncertainties in order to engage in science practices to make sense of a phenomenon, idea, or concept). As such, in the observed lessons, the teachers rarely used student uncertainty as a resource. Instead, they used student uncertainty as a prompt to re-explain concepts and ideas, or structured lessons to reduce potential uncertainties. In essence, teachers treated student uncertainty as a barrier to be removed. As such, reductions of uncertainty were the most commonly observed navigation strategy; teachers rarely integrated raising, maintaining, or postponing uncertainty (See Table 5). In fact, reducing uncertainty was the only navigation strategy used by all 14 teachers; the strategies of raising and maintaining uncertainty were each used by only eight teachers. Moreover, the average proportion of time spent reducing uncertainties per classroom observation was 54%, more than twice the time spent maintaining or raising uncertainties combined.

Only eight teachers raised uncertainty at all during their observed lesson, five of whom raised uncertainty only once, and the average percentage of class time spent raising uncertainty was 6% of the total lesson. Maintaining uncertainty was also less prominent, with the average time of 13% of the total lesson spent using this strategy. As teachers did not explicitly invite students to express uncertainty within the observed classroom lessons, students did not raise uncertainties that would need to be postponed; thus postponement was not observed or included in the table.

To explore *how* uncertainty navigation strategies were sequenced throughout each classroom observation, we mapped the temporal relationship of teachers' enactment for each observed lesson. As exhibited in the temporal maps (See Fig. 1), the majority of teachers attempted to raise uncertainty (indicated by shades of green), then immediately reduce it (indicated by shades of red), limiting the pedagogical use of raising uncertainty to begin with and adding to the fractured uncertainty navigation pathways. Within the temporal maps, shading indicates the level of score associated with each navigation strategy. Chunks of temporal time where teachers were explaining classroom routines or task instructions for close-ended tasks not tied to science instruction were labeled as "NONE" (e.g., Ishana asked students to complete a warmup questionnaire focused on how students were feeling; Ash and Cameron incorporated breathing and meditation into their classroom routines).

There were only two instances across the dataset where teachers (i.e., Ishana and Fin) continued to maintain uncertainty after instances of raising it (indicated by shades of yellow following shades of green). As one example, we offer a classroom excerpt (See Table 6) that starts with Fin raising uncertainty at the beginning of their lesson as a way to problematize a phenomenon (i.e., asking students what they think

Table 5
Teacher use of uncertainty navigation strategies within classroom observations.

Teacher	Event occurrence at the macro level / Proportion of time spent in each uncertainty navigation strategy		
	Raise	Maintain	Reduce
Cameron	1 / 7%	0	5 / 65%
Ash	0	2 / 8%	2 / 36%
Jessie	2 / 13%	2 / 29%	5 / 42%
Ishana	1 / 3%	1 / 27%	2 / 50%
Shaye	1 / 13%	1 / 2%	3 / 75%
Zion	2 / 26%	1 / 36%	3 / 15%
Charlie	1 / 4%	0	5 / 81%
Indigo	1 / 3%	0	3 / 91%
Marley	0	0	3 / 68%
Kyler	0	3 / 12%	3 / 34%
Fin	2 / 7%	3 / 25%	5 / 49%
Esme	0	0	3 / 43%
Addison	0	2 / 24%	4 / 50%
Mean percent	6%	13%	54%

Note. Scores do not add up to 100% as there were temporal events of "no uncertainty" within the observed lessons.

Table 6
Excerpt from Fin's event of maintaining uncertainty after raising it.

Turn	Speaker	Excerpt from Fin's observed lesson	Physical actions in classroom
1	Teacher	"Do we understand that we can't make energy, you can't destroy energy?"	Teacher had posted a picture of a car crash while problematizing energy transfers
2	Student 1	"You *can* make energy"	
3	Teacher	"Okay, let's argue. ((pauses)) She [Student 1] said, 'but you can make energy"	Teacher moves closer to students and stands off to the side as they invite the rest of the class to debate the idea of the law of conservation of energy
4	Student 1	"Cause you *can*"	
5	Multiple students	"Yeah you can make energy"	
6	Student 2	"What about static electricity?"	
7	Student 1	"You make energy when you rub your hands like this"	Student 1 physically moves her hands as if rubbing a balloon
8	Student 3	"Yeah I've done that"	
9	Teacher	"Let's challenge this. ((muffled students talking at once)) She's saying you can make energy with static electricity. Well let me ask you a question - in order to make static electricity, did you have to move?	
10	Multiple students	"Yeah …"	Some students hesitated, tilting their head and scrunching their faces (physical signs of uncertainty; Hübscher et al., 2017)
11	Teacher	"So you're either rubbing your feet, right? Doing a little shuffle"	Teacher physically moves as he describes the action (rubbing feet on the floor)
12	Student 4	"I think so"	
13	Student 1	"Or you're rubbing a balloon"	
14	Teacher	"Or you're rubbing a balloon on your head or another surface. So am I moving to create the energy?"	Teacher points to student who suggested a balloon and physically modeled that action
15	Multiple students	"Yes"	
16	Teacher	"So am I creating energy or am I transferring the energy from me, my food, my chemical energy, am I changing that into static?"	
17	Multiple students	"Oh"	
18	Student 1	"You're transferring your energy"	
19	Teacher	"Ohh. Is there another example that you can think of where you're creating energy? ((pause)) Let's talk about it, can anyone do it? ((pause)) You get on the bike with a generator and you're peddling, are you making energy or transferring it?	Student starting to collectively realize the different between transferring energy and creating energy as they look around the room and can't add another example of creating energy
20	Multiple students	"Transferring energy"	
21	Student 1	"Cause you're using the pedals and then the pedals add to the energy generated"	Student 1 uses her hands to motion the pedals circulating while other students have side chatter

Note. Italics in the excerpts represents additional emphasis placed on the word by the speaker.

energy transfer means).

Fin attempts to problematize the concept of energy transfer by showing an image of a car crash and making a claim that energy cannot be made or destroyed (Turn 1). When Student 1 disagrees (Turn 2), the teacher realizes a potential misconception and asks the class to debate this idea. Throughout this event, the teacher uses student uncertainty to drive the lesson, inviting students to add and compare their ideas as they debate this particular science concept.

This excerpt is used as an example of the teacher guiding the construction of ideas by providing the explanations and reasoning instead of asking students to explore the topic more as a strategy to identify their own misconceptions and construct their own understanding (the law of conservation, as seen here). Thus, while Fin asked for student ideas and opened opportunities to disagree, debate, and challenge ideas, they eventually took back control to guide students to the correct understanding.

As seen above (Tables 4 and 5; Fig. 1), the ways teachers structured their lesson involved a high proportion of class time attempting to reduce uncertainties, with minimal opportunities to invite students to maintain or increase their uncertainty throughout the lessons. In addition to creating teacher-constructed storylines, the resulting fractured uncertainty navigation pathways limited opportunities for students to connect ideas about the phenomenon at hand and put the focus on restating knowledge given from the teacher or text. The three teachers who used strategies to raise uncertainty more than one time across their lessons (i.e., Jessie, Zion, Fin) still ended their lesson with reduction strategies. Thus, uncertainty was primarily raised only to increase engagement and spark curiosity.

4.2.2. *Surface-level reduction strategies*

Adding to the fractured uncertainty navigation pathways (see Fig. 1), teachers did not use any higher-level reduction strategies (i.e., no events were scored as a 3 based on the rubric in Table 3). For example, as Charlie was teaching about the digestive unit, they instructed students to read an informational article in their table groups and discuss the answers to questions on a given worksheet. Instead of letting students wrestle with the information to unpack their understanding and reduce uncertainties on their own, the teacher went on to explain where to find each answer,

> I'm gonna tell you some hints. Number 1 is found in paragraph 2. Number 2 is found in paragraph 4. Number 3 is found in paragraph 6 … Now, I'm going to tell you that none of these are word for word, so it's better to read the entire article … You're going to have to read, think about it, and make connections and try to find the answers. At the end, we'll go over the answers together.

In this excerpt, and several similar observed lessons, Charlie reduces uncertainty before students are given a chance to generate or raise uncertainties. They step in before students start the learning task to narrow the focus on searching for the correct answers in specific locations in the article. While they direct students to make connections on their own, Charlie decreased the students' work-load and used surface-level reduction strategies to eliminate the potential for uncertainty (scored as a 1).

Teachers were commonly observed reducing uncertainty by heavily scaffolding directions and providing students with answer keys or word banks before they were given a chance to grapple with the concept or their interpretation of the concepts. As such, most of the scored reductions across the observations involved teachers delivering answers without asking students to expand their own thinking or explain their reasoning (e.g., reading answers to a worksheet out loud, explaining concepts prior to students wrestling with their own understanding).

4.2.3. Missed opportunities in facilitation of uncertainty navigation strategies

Across the observed lessons, teachers missed opportunities to support students to further navigate their uncertainty and engage in productive struggle, including events where teachers attempted enactment of uncertainty navigation strategies but did not follow through (i.e., fractured uncertainty navigation pathways). In particular, teachers missed opportunities to raise and maintain uncertainty.

Missed Opportunities to Raise Uncertainty. Half the teachers did raise uncertainty and invite students to question, predict, and imagine different scenarios throughout the observed lessons. However, the next move was typically to give students the answer, thus reducing potential for further unpacking uncertainty. For example, beginning a lesson on Earth's systems, Cameron showed a video of an experiment to help explain convection currents. Before starting the video, Cameron asked students to predict what would happen in the experiment and then instructed them to write down observations, telling students, "fill out the paper as you go and I'll pause [the video] and tell you what to fill out". This framing (i.e., "tell you what to fill out") takes responsibility away from the students and adds to the teacher-constructed storylines and fractured uncertainty navigation pathways. Throughout this episode, Cameron paused the video to ask questions and invite students to talk in teams in order to write down answers on their worksheets. She then called on students to share their predictions (See Table 7).

The teacher initially posed a question to problematize the phenomenon as a cursory exploration. While students did make predictions, they were not given opportunities to explain, reason, or develop their initial ideas. When Student 2 struggled to make a guess after stating she didn't know (turn 8), the teacher quickly gave her options to use as her guess (turn 9), reducing the struggle. In this missed opportunity to raise uncertainty, Cameron could have challenged partners to debate what would happen or encouraged Student 2 to talk through her thought process. Eventually another student chimed in to help rephrase Student 2's idea (turn 13). While the teacher did not validate responses by saying yes or no to either prediction, they missed an opportunity to problematize the phenomenon further and invite students to generate new wonderings or discuss uncertainties. These missed opportunities were also common in other teachers' observations, as they attempted to raise uncertainty by problematizing a phenomenon, but limited opportunities for students to further develop their ideas.

Missed Opportunities to Maintain Uncertainty. Eight of the teachers attempted to maintain uncertainty within their lessons; however, they missed opportunities to invite students to explain their reasoning or interpretations, or debate, critique, or question ideas. For example, Jessie, the only teacher in this study to explicitly design their lesson using student-generated inquiry questions, attempted to organize a discussion after small groups had researched information about their questions. Jessie invited students to discuss their ideas stating, "this is a discussion to learn the questions we still have doubts about". However, as the groups started to present their ideas, Jessie asked students to hold onto their questions and not talk during that portion. Following each group's presentation, Jessie summarized or paraphrased a portion of the group's ideas to the class (e.g., "I want to add to that …"; "Okay, so you focused on coal …"). Once all groups had presented, Jessie invited the class to ask questions and have a discussion, but no one spoke. So although they structured this portion of the class to be a discussion, Jessie minimized opportunities while students were sharing ideas, taking more control over the structure and storyline. Further, as Jessie recapped each groups' presentations, the opportunity to maintain uncertainties was eliminated. Thus, while this event was set up to maintain uncertainties with a debate, it was scored as a reduction of 1 due to Jessie's taking control of the dissemination and interpretation of information.

5. Discussion

Overall, there were several aspects that aligned between teachers' perceptions and practice of using student scientific uncertainty as a pedagogical resource, described below. Broadly, the perceptions of uncertainty the teachers held demonstrated a limited awareness of the potential that desirable uncertainty can have as a resource in science

Table 7
Episode from Cameron's missed opportunity to raise uncertainty.

Turn	Speaker	Excerpt from Cameron's observed lesson	Actions in classroom
1	Teacher	"2 people, raise your hand and tell me what you think is going to happen to the blue water. [Student 1]"	Video was paused prior to pouring in the cold, blue liquid; Students were asked to predict what they think would happen to the blue liquid.
2	Student 1	"I think it will go lower than the warmer water because cold sinks."	
3	Teacher	"Okay, so you think cold will sink and it will go down, or more down than the warmer water. Okay, does anyone else have a different idea, different, not the same? [Student 2]"	
4	Student 2	"Um, I'm pretty sure that it might go warmer cause, I don't know, heat is really overpowering. Or, they'll mix together"	
5	Teacher	"Okay, so it will eventually even out?"	
6	Student 2	"Yeah it'll eventually mix"	
7	Teacher	"But what's gonna like right when she puts it in? (.) Where is that cold water gonna go? Where do you think?"	
8	Student 2	"I have no idea"	
9	Teacher	"You have no idea. Why don't you just guess? (.) Up, down, right, left? Nowhere; it will stay in there. Where?	Student hesitated guessing, Teacher waited 3 s before offering answers.
10	Student 2	"Um it'll mix in there"	
11	Teacher	"So it's gonna go up? Is that what you think? Is it gonna move up?"	
12	Student 2	"No? I don't know"	
13	Student 3	"No, she's saying like when she puts it in, it just kinda mixes"	
14	Teacher	"It just kinda mixes, okay. Let's see what happens"	Resumes video

teaching; as such, this awareness led to fractured uncertainty navigation pathways within their enacted lessons.

Valuing Initial Curiosity but Need to Reduce at the End of a Lesson. All teachers in this study acknowledged the benefit and importance of embedding uncertainty into their science classrooms. However, this value was restricted primarily to raising interest or sparking initial curiosity to engage students in instruction, expressing the need to reduce any residual uncertainties by the end of that lesson. These perceptions aligned with practice in that the eight teachers who raised uncertainty within their observed lesson did so as a way to elicit interest by problematizing a phenomenon; however, they shifted quickly to reduce or eliminate possible uncertainty that was raised. Furthermore, all lessons, with the exception of one (i.e., Ishana), ended with teachers attempting to reduce uncertainties.

It is common and understandable for teachers to feel the need to resolve student uncertainties, especially due to the expectations of standardized testing and scheduled curriculum guides that push teachers to silo lessons and instruction into discrete, time-bound units. However, when teachers prioritize reducing or eliminating uncertainties, they may miss opportunities to invite students to generate elaborative storylines related to science phenomenon, critique or debate ideas, develop experiments to test their researchable questions, and build deeper connections with learning content (Hiebert & Grouws, 2007; Warshauer, 2015). Nonetheless, this is a common practice as teachers may use uncertainty as a place-holder activity instead of problematizing phenomena throughout instruction and driving student scientific storylines (Manz & Suárez, 2018). Student scientific uncertainty can be used to foster or induce interest and curiosity during science instruction, both of which are valuable resources in science learning (Lamnina & Chase, 2021; Ozcelik et al., 2013). However, constricting uncertainty's use only to engagement or wonder at the beginning of a topic may limit how students engage in science practice throughout an inquiry process.

Valuing Struggle but Not Knowing How to Foster it. A second alignment between perceptions and practice surrounds how teachers value and foster struggle. Reductions of uncertainty were the most commonly used uncertainty navigation strategy. Moreover, the reductions were primarily surface-level as teachers gave answers promptly at the first sign of struggle or asked students to summarize given information. Reducing uncertainty is not a poor strategy; in fact, reducing uncertainty can help lower stress as new knowledge is gained (Brashers, 2001; Jordan, 2015). However, there is a difference between inviting students to reduce their own uncertainty and reducing it for them. While there are benefits of scaffolding support and providing resources to struggling learners, challenging students to extend their understanding of the phenomenon and providing opportunities to struggle or grapple with their uncertainties can improve sense-making skills and build students' deeper understanding of science concepts (Reiser, 2004).

Responding to curriculum and pacing guides required in many science teaching contexts, teachers need to fit their instruction within specific time constraints, and it is reasonable for teachers to want to make sure their students understand information presented. However, there are other strategies to support students' reduction of uncertainty (e.g., using familiar phenomenon-based examples to guide students' understanding, inviting students to conduct research, using their ideas to drive collaborative discussions). Furthermore, our results reaffirm previous studies identifying the tension teachers face including: (a) fostering students struggling with desirable uncertainties for the sake of developing resilience (Polirstok, 2017; Russo et al., 2020), while (b) acknowledging the possibility that struggling with undesirable uncertainties can decrease students' motivation and self-confidence, prompting frustration and withdrawal (Anderson, 2006). This tension can lead teachers to avoid uncertainty entirely and over-scaffold learning experiences for students (Beghetto, 2017), especially when the uncertainty is not acknowledged or perceived as a beneficial element in the classroom.

Perceptions of Content Uncertainty Led to Fractured Uncertainty Navigation Pathways. Finally, teachers' limited awareness of types and sources of uncertainty in science learning led to fractured uncertainty navigation pathways. As the teachers largely identified uncertainty stemming from a lack of content knowledge, they overlooked epistemic uncertainty related to *how* students come to know using scientific practices (e.g., how to make observations, define problems, plan and carry out investigations, argue from evidence), which can prompt students' pathways of learning through developing scientific storylines around problematized phenomena. Within enacted lessons, students' expressions of uncertainty provided the impetus for teachers to remedy that uncertainty by providing quick or additional content knowledge, aligning with teachers' perceptions. However, not knowing is not the same as being uncertain; the former denotes a lack of knowledge, while the latter requires recognition of some degree of being unsure or unclear (Smithson, 1989).

Similarly, several teachers expressed checking for understanding as a way to identify students' sources of uncertainty, without reflecting on or interrogating possible alternative sources of student uncertainty (e.g., uncertainty stemming from incoherence associated with students' inability to disentangle complicated or complex ideas or possible action sequences in multi-step scientific processes; Chen & Qiao, 2020). With a richer perceptual recognition of possible sources of uncertainty, checks for understanding could be supplemented or replaced with checks for uncertainty. In essence, teachers could ask students to raise, or identify and acknowledge uncertainty they are currently experiencing in relation to a science lesson or unit. This strategy could then create an opportunity to recognize what is currently unknown and determine a pathway to address the given uncertainty. Teachers' focus on content uncertainty and narrowing in on only one potential source of student uncertainty, added to their limited awareness of the potential use uncertainty could play in science learning.

Within lesson enactment, uncertainty was used as a resource for teachers to lecture and provide information, instead of being used as a resource for students to develop their own understanding or chart a course for how to come to understand a given phenomenon or concept. Even when teachers invited students to ask questions throughout their lessons, they ultimately took more control, steering student questions toward the teacher's predetermined plan (i.e., *pseudoagency*; Miller et al., 2018), limiting options for students to explore different pathways or ideas. We are encouraged by teachers' use of navigation strategies (e.g., evidence of raising and maintaining uncertainty intermittently in a few lessons), but observed gaps demonstrate room for growth.

5.1. Implications for teacher education and professional development

Uncertainty is a pervasive experience in science learning (Kirch, 2010; Ko & Luna, 2023; Phillips et al., 2017), and scholars have argued that professional development experiences could help teachers reflect on their practice and learn to manage or even welcome or embrace uncertainty (Gideon et al., 2022; Lefebvre et al., 2023; Snow-Gerono, 2005; Starrett et al., 2022). Thus, coupling previous scholarship with the findings of the current study, we argue that professional learning experiences are needed to support teachers in understanding potential uses of uncertainty in science classrooms, as well as how purposeful uncertainty navigation is beneficial for student learning. Moreover, such opportunities are needed both for practicing teachers and pre-service teachers, as existing teacher preparation programs do not currently emphasize strategies for using student uncertainty as a pedagogical resource to help students develop knowledge and engage in scientific practices.

Educational researchers, teacher educators, and designers of teacher professional development might benefit from considering ways to expand teachers' awareness that sources of student scientific uncertainty extend beyond content knowledge to include epistemic knowledge (Lee et al., 2023) related to how students bring scientific practices to bear on creating and implementing plans of action to interrogate scientific phenomena. In other words, professional development experiences could help in-service and pre-service teachers (a) recognize multiple sources and types of students' uncertainty (b) acknowledge the ways that different sources of uncertainty can be desirable, and (c) develop strategies and instructional tools to support students in using uncertainties to understand content, frame researchable questions, design experiments, and develop arguments, among other scientific practices.

In particular, there is a need to build teachers' awareness of a greater range of scientific uncertainties that their students may experience, including content *and* epistemic uncertainties, as well as understand multiple ways uncertainty can be desirable. If a teacher does not recognize the desirability of uncertainty as a driver of students' quest for deeper understanding of scientific phenomena, their ability to help students build coherent storylines likely remains low (see also, Manz & Suárez, 2018; Watkins et al., 2017). Thus, opportunities to engage in professional development that explicitly addresses uncertainty can provide both an awareness and strategies to use uncertainty as a resource in science learning.

5.2. Limitations

Although the results of the current study serve as a baseline of science teachers' perceptions and practice related to navigating student scientific uncertainty, specifically in United States education contexts, they do not provide adequate grounding to fully develop strategies for teacher education and professional development programs globally. Thus, future research should investigate how to design effective professional learning experiences in various regions that support teachers at all levels in developing their capacity to use student uncertainty as a resource in the science classroom.

Additionally, the classroom observations conducted in this small-scale study entailed only a single classroom observation from each teacher, yet, science learning does not take place in discrete lessons; it unfolds over a set of experiences focused on a specific scientific phenomenon. Case studies of how teachers navigate uncertainty in the classroom could help further explore the relationship between planning and enacting, and how both these activities are shaped by teacher perceptions over the course of a unit.

6. Conclusion

Science practice introduces inevitable uncertainties; thus, teachers need to understand and work with students struggling with uncertainties during science learning. Although the teachers in this exploratory study recognized that uncertainty could be desirable in the science classroom, both their perceptual and enacted responses exhibited only a narrow band of desirability, creating a fractured uncertainty navigation pathway. Teachers perceived uncertainty as a way to induce curiosity and persist through struggle; however, they were quick to reduce uncertainty and provided limited space for students to productively struggle while engaging with science phenomena. Teachers have the opportunity to shift students' trajectory of scientific uncertainty, therefore, it would be beneficial to support teachers in understanding strategies that foster productive uncertainty navigation pathways.

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CRediT authorship contribution statement

Emily Starrett: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Michelle Jordan:** Writing – review & editing, Writing – original draft, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Ying-Chih Chen:** Writing – review & editing, Writing – original draft, Methodology, Funding acquisition, Conceptualization. **Jongchan Park:** Writing – review & editing, Visualization. **Carlos Meza-Torres:** Writing – review & editing, Visualization, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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