Research in Science Education (2024) 54:359–391
https://doi.org/10.1007/s11165-023-10144-3

Conceptualizing Phases of Sensemaking as a Trajectory for Grasping Better Understanding: Coordinating Student Scientific Uncertainty as a Pedagogical Resource

Heesoo Ha[1] · **Jongchan Park**[2] · **Ying-Chih Chen**[2]

Accepted: 9 November 2023 / Published online: 4 December 2023

Abstract

Sensemaking is conceptualized as a trajectory to develop better understanding and is advocated as one of the fundamental practices in science education. However, the field is lacking of a framework to view the prolonged process of sensemaking that starts from a raise of uncertainty of a target phenomenon to a grasping of a better understanding of a target phenomenon. The process requires teachers to recognize the role of scientific uncertainty in different phases of sensemaking and develop responsive instructional supports to help students navigate the uncertainties. With an attention on student scientific uncertainty as a potential driver of the trajectory of sensemaking, this study aims to identify different phases of sensemaking that can be developed with students' scientific uncertainty. This study especially attends to two types of scientific uncertainty—conceptual and epistemic uncertainties. Conceptual uncertainty refers to student struggle of using conceptual understanding (e.g., mastery of content and everyday knowledge) to respond to an encountered phenomenon. Epistemic uncertainty emerges from struggles in using epistemic understanding to generate new ideas. Based on the multiple case study method, we examined sensemaking activities in two Korean science classrooms and one American science classroom and identified three phases of sensemaking: (a) focusing on a driving question related to a target phenomenon, (b) delving into multiple resources to develop plausible explanation(s), and (c) examining the successfulness of the new understanding and concretizing it. Based on the findings, we discuss two emerging themes. First, sensemaking progresses through three distinctive phases driven by students' dynamically evolving scientific uncertainty. Second, attending to both epistemic and conceptual uncertainties can support developing sensemaking coherent with students' view.

Keywords Sensemaking · Phases of sensemaking · Uncertainty · Scientific uncertainty · Pedagogical resources

✉ Heesoo Ha
snudunoy717@snu.ac.kr

[1] Center for Educational Research, Seoul National University, Gwanak-Ro 1, Gwanak-Gu, Seoul 08826, Republic of Korea

[2] Mary Lou Fulton Teachers College, Arizona State University, Tempe, AZ, USA

Introduction

The fundamental goal of scientists' practices is described as sensemaking of the natural world, which refers to a process of grasping better understanding of how phenomena occur (Odden & Russ, 2019; Schwarz et al., 2017). Sensemaking is considered as a trajectory in which students engage in problematizing phenomenon to generate a guiding question, identifying gap in their existing understanding, gathering and evaluating potential resolutions, and grasping a more coherent understanding that resolves the gap (Klein et al., 2006; Naumer et al., 2008). However, traditional teachers often consider sensemaking as piecemeal moments of sudden realization, recognition, or comprehension. In this traditional perspective of sensemaking, students have less opportunities to actively build coherent understanding. Piecemeal realization, recognition, or comprehension is likely to result in fragmented understanding rather than building coherent connections between prior and new understanding. To provide ample opportunities for students to reflect on what they do not understand and why, as well as how to figure something out by their own, it has been argued that teachers need to support building the trajectory of sensemaking coherent with students' perspective (Sikorski & Hammer, 2017; Reiser et al., 2021; Roth et al., 2011).

However, enacting sensemaking as a trajectory for developing better understanding in the science classroom remains two issues to be resolved. First, what are essential phases that constitute the trajectory of sensemaking in science classroom? That is, what are necessary phases that students go through in order to grasp better understanding? This issue indicates a necessity to examine how sensemaking can progress in the science classroom.

Second, whose sense do students make? What drives or motivates the trajectory of sensemaking? Scholars suggested that student ideas play a critical role in shaping the direction of sensemaking and opening space for discussion (e.g., Reiser et al., 2017). However, utilization of student ideas alone is not sufficient to invite students to actively engage in understanding what does not make sense to them and how to develop their own "sense" of the problems. Recently, several scholars argued that student scientific uncertainty can be a vital resource to drive the trajectory of sensemaking and help students construct meaningful explanations to develop their own sense of an encountered phenomenon (e.g., Chen, 2020; Watkins & Manz, 2022). We adapt this view and conceptualize student scientific uncertainty as a pedagogical construct that teachers can use and design in sensemaking activities to drive students to actively develop their own sense and better understanding. Nevertheless, few studies have examined the varied roles of student scientific uncertainty as a pedagogical resource in the trajectory of sensemaking.

Therefore, this study aims to address the two issues by identifying phases of sensemaking and the role of scientific uncertainty as a pedagogical resource that drives each phase. This work can provide a general framework of sensemaking that can be used by teachers to anticipate how sensemaking can develop and decide instructional moves to elicit and respond to students' scientific uncertainties. The specific research questions are as follow:

1. What are the essential phases of sensemaking of target phenomena?
2. What are the roles of scientific uncertainty as a pedagogical resource in each phase of sensemaking?

Background of the Study

Sensemaking as a Prolonged Trajectory Rather than Fragmentary "Aha!" Moments

Sensemaking in science classroom can be described as a cumulative, sequential, and ongoing trajectory in which students identify the gap of their existing understanding toward explaining a phenomenon, generating a driving question to explore the gap, exploring plausible resources to solve the gap, and enacting the best solution to evaluate their newly developed understanding (Cannady et al., 2019; Odden & Russ, 2019). Traditional teaching often treats sensemaking as several fragmented and surprising "aha!" moments where teachers instantly feed information to students (Gooding & Metz, 2011). Students may have a moment to make "sense" of the explanation provided by teachers, but it is difficult to view this moment as students continuously engaging in "figure something out" to develop their own better understanding. That is, meaningful sensemaking requires students to actively and continuously construct new understanding or explanation based on what they know and what they do not know, rather than passively receive information from teachers or textbooks.

Sensemaking involves a series of explanation construction processes. However, sensemaking is not equivalent to explanation construction (Flood et al., 2015; Odden & Russ, 2019). Building on the definition of sensemaking articulated by Odden and Russ (2019), sensemaking involves grasping *new* understanding; explanation may not necessarily involve students in developing *new* understanding. For example, students can engage in explaining their preassembled mental model without a necessary of making sense of any new information or alternative ideas. In this kind of explanation activity, students can use a variety of reasoning skills (e.g., mechanics, inductive, deductive) to construct a robust explanation "without the need for any new knowledge or connections" (Odden & Russ, p. 198). In contrast, sensemaking requires students to restructure and refine their existing understanding in order to develop new and coherent understanding to explain a target phenomenon.

To support students' active engagement in making sense of target phenomena, it is argued that the trajectory of sensemaking needs to be developed with students and coherent with students' perspective (Sikorski & Hammer, 2017; Reiser et al., 2021; Roth et al., 2011). To build such a trajectory, several researchers emphasized the importance of identifying the "need" of students (Sikorski & Hammer, 2017). Scholars argue that unless teachers can recognize the need and design the sensemaking trajectory in relations to the need, sensemaking is unlikely to be a meaningful process for students (Engle & Conant, 2002). This perspective of designing meaningful sensemaking raises a critical question: What is the need to motivate students to actively engage in the process of sensemaking for grasping better and coherent understanding?

Student Scientific Uncertainty as a Need that Motivates Sensemaking

Scientific knowledge that makes sense of the natural world develops further in scientists' efforts to resolve their uncertainty, which means that scientific uncertainty indicates what aspects of a particular knowledge can improve and becomes an impetus of the development of scientific knowledge (Jordan and McDaniel, 2014; Star, 1985). Similarly, along a trajectory of sensemaking, students are expected to encounter scientific uncertainty, which can be a “need” that drives the trajectory of sensemaking. Scientific uncertainty in science classes involves struggle to understand and/or decide what and how to investigate, how explanations can be justified, and how explanations can be used to solve real-world problems (Kampourakis, 2018). Attending to such student scientific uncertainty helps construct a sensemaking trajectory coherent with student perspective (Manz, 2015; Tekkumru-Kisa et al., 2020; Watkins & Manz, 2022). For example, Watkins and Manz (2022) demonstrated that student scientific uncertainty has potential to create meaningful space for students to re-evaluate their understanding of encountered phenomena, discuss their potential gap of inconsistency, and pursue deep understanding to interpret the phenomena. Metz (2004) showed that students had opportunities to develop more coherent understanding of target concepts when their uncertainties are manifested as a means to drive the process of sensemaking. Building on the perspective of cognitive thinking, Tekkumru-Kisa and colleagues (2020) argued that using student scientific uncertainty can sustain cognitive demand on students’ thinking in sensemaking because it facilitates them to engage in productive struggle. They advocated that student uncertainty is a critical element associated with student struggles in developing their own sense of the natural world.

Two Types of Scientific Uncertainty: Conceptual and Epistemic Uncertainties

We focus on two types of scientific uncertainty—conceptual uncertainty and epistemic uncertainty—based on the emphasis on conceptual and epistemic understandings as two key dimensions of understanding in learning of science (Ford & Wargo, 2012; Osborne, 2014). Conceptual uncertainty refers to students’ being unsure and struggling about using content and everyday knowledge of the world (Chen & Qiao, 2020; Chakravartty, 2017; Kampourakis & McCain, 2020). Epistemic uncertainty refers to students’ struggles in using epistemic understanding to contrive how to generate and justify knowledge—specifically, when formulating questions, generating and interpreting data to construct better understanding (Beven, 2016; Kirch, 2009; Sensevy, 2014).

In sensemaking, students are expected to experience conceptual uncertainty as they gather information from various knowledge sources. Epistemic uncertainty plays a critical role in building a process that leads to the development of new knowledge. Literature (e.g., NRC, 2012) criticized traditional science classroom to be over-emphasizing conceptual uncertainty and argued for epistemic uncertainty to be managed in sensemaking. This is because phenomena explored in science and science classroom are usually complex in that sensemaking of phenomena requires more than a piece of information. While we agree with this argument, we also view that conceptual uncertainty is another key scientific uncertainty to be managed to collect resources to use in developing new knowledge. Therefore, this study attends to both conceptual and epistemic uncertainties as main resources for building the sensemaking in the science classroom.

Coordinating Student Scientific Uncertainty as a Pedagogical Resource to Construct the Trajectory of Sensemaking

Scientific uncertainty has been recently emphasized as a potential pedagogical resource that can be used to promote students’ engagement in sensemaking (Chen et al., 2019; Manz, 2015; Watkins et al., 2018). Studies suggested several teaching strategies related to student scientific uncertainty (Chen & Techawitthayachinda, 2021; Rapkiewcz et al., 2023; Manz, 2018; Manz & Suárez, 2018). For example, Manz and Suárez (2018) suggested ways to embed scientific uncertainty in curricula so that students can engage more in scientific practices and grapple with the uncertainties, for example, beginning instruction with a complex phenomenon and leveraging variability in student ideas. Chen and colleagues (Chen & Qiao, 2020; Chen & Techawitthayachinda, 2021; Chen, 2022) emphasized the roles of scientific uncertainties in developing understandings through scientific practices and suggested teaching strategies to support students to manage their uncertainties (e.g., cycles of raising, maintaining, and reducing scientific uncertainties). Similarly, Manz (2018) argued that teachers should deliberately put efforts on managing student uncertainty to be productive for students' sensemaking. Strategies for making uncertainty productive included allowing students to experience uncertainty during scientific practices, bounding uncertainty to avoid overwhelming uncertainties, and making student uncertainty public.

These studies indicate that student uncertainty can be used pedagogically for students' productive sensemaking. However, their views on the role of uncertainty in facilitating student sensemaking were limited in unpacking different roles of uncertainty in different phases of sensemaking. It is unclear, for example, how scientific uncertainty emerging during the introduction of a complex phenomenon can differ from uncertainty that arises in the middle of student discussion to develop a new understanding of the phenomenon. It is also not clear how scientific uncertainties manifest in distinctive ways across trajectories of sensemaking. A limited understanding about these issues leads to difficulties in using scientific uncertainties as pedagogical resources. In other words, teaching strategies related to student scientific uncertainty were identified with limited attention to differences in roles of student scientific uncertainty along the trajectory of sensemaking. This study aims to address this issue, examining how student scientific uncertainty can be used to support student management of it and subsequently, engagement in the trajectory of sensemaking.

Method

This study adapted the multiple case study method (Merriam, 1998), which suggested that by a cross-case analysis of multiple cases, more generalized interpretation across the cases can be achieved. This study aimed to examine how sensemaking develops and what roles scientific uncertainty can play as a pedagogical resource in various cases of sensemaking.

Research Context and Participants

To bring findings that hold broader implication, this study examined sensemaking activities implemented in American and Korean science classrooms. This study was designed as a follow-up to our initial explorations of argumentation that were designed and implemented to help student make sense of phenomenon in South Korea and US contexts by first and third authors (Chen, 2020; Chen et al., 2019; Cho et al., 2019; Ha & Choi, 2023), respectively. Specifically, in this study, we focused on activities in three science classrooms, two in South Korea and one in the USA. The main characteristics of teachers and the number of students in the three classrooms are described in Table 1. There were 24–29 students in each classroom. In the two Korean classrooms, students formed 7–8 groups, each with four to five students. Each student group is defined as a case in this study because each group developed distinctive process of sensemaking through group discussion after a teacher's introduction of a target phenomenon.

Activities implemented in the three classrooms commonly aimed to encourage students' active engagement in the development of explanations of target phenomena through

Table 1 Description of participating teachers, their students, and implemented curriculum

Teacher participants	Country	Teaching experience	Student grade	The number of students (the number of groups)	Main concept	The number of lessons (length of each lesson)	The number of episodes
Ms. Kim	South Korea	10 years	Seventh grade	28 (8 groups)	Photosynthesis and transpiration of plants	7 lessons (90 min)	63 episodes
Ms. Hong	South Korea	16 years	Seventh to ninth grades	29 (7 groups)	Ecosystem	8 lessons (90 min)	11 episodes
Ms. Jager	USA	10 years	Fifth grade	24 (6 groups)	Respiratory system	6 lessons (50 min)	11 episodes

argumentation. Researchers provided the teachers with target phenomena that teachers can use to design activities in each unit, along with the following design principles in common: (a) engage students in the development of arguments regarding how a target phenomenon occur and (b) engage students in social negotiation of their arguments to reach a consensus. In the activities, the teachers provided target phenomena and discursive supports to facilitate students' engagement in the activities. The teachers were asked to apply the design principles in their lessons. Researchers collaborated with teachers before and during the lessons to support the application of the principles in the development of each activity.

The teachers commonly began each activity by introducing a target phenomenon, accompanied by a driving question aimed at guiding students in making sense of the phenomenon. Subsequently, whole-class or group discussions were conducted where students shared their initial thoughts and collaboratively constructed a more coherent understanding of the target phenomenon. Throughout the process, the teachers provided support to students in collecting data and evaluating their ideas, actively engaging in student discussions as another participant contributing to the synthesis of new ideas. The activity ended with whole-class discussion where students developed an agreed understanding of the target phenomenon.

Although specific contexts varied, we found that the common design principles led the three classrooms to hold similarities, especially in terms of how the teachers encouraged students' active engagement in sensemaking and how student scientific uncertainty were used as pedagogical resources. Thus, by identifying commonalities among multiple cases, we aimed to bring broader findings in our search for the role of scientific uncertainty in the development of phases of sensemaking.

Data Collection and Analysis

The primary data sources of this study were video recordings and transcripts of classroom discourse. These data sources were utilized due to the study's focus on understanding the role of scientific uncertainty as a pedagogical resource, specifically by examining how uncertainties were coordinated within classroom discourses (Mercer & Littleton, 2007; Scott et al., 2006). Studies by Warren et al. (2001), Watkins and Manz (2022), Haverly et al. (2020), Furberg and Silseth (2022), and Lowell et al. (2022) focusing on sensemaking or uncertainties in classroom discussion suggested that video recordings provide rich data sources to understand the exchange of ideas and uncertainty among students and teachers by interactions. Through analyzing the interactions, the evidence of how uncertainties are used and how students develop better understanding can be potentially revealed. While student interview data could provide additional evidence to verify whether students make sense of certain issues, this is not the objective of the paper, and interviewing every student at the moment to make sure if they make sense would be challenging. That is, the objective of the study is to understand how student uncertainties are leveraged as a pedagogical resource to develop better understanding during class discourse. In the analysis of discourse data, only the utterances in which students explicitly expressed their uncertainty, confusion, and comprehension of a phenomenon, issue, or idea were identified as the situations in which students wrestle with uncertainties and develop better understanding. Other auxiliary data used in this study include student-created artifacts, such as student worksheets, student-created physical models, and experimental settings. These data were used to understand the context of activities and additional evidence of how student uncertainty was used as a pedagogical resource.

Data analysis was conducted in four steps. We first iteratively watched the video recordings along with reading transcripts of the recordings to grasp overall classroom activities. Then, we divided the activities in each classroom into episodes, which we defined as beginning with an introduction to a target phenomenon and ending with students' development of an agreed explanation of the given phenomenon. There were trajectories of discussions that did not reach a development of shared understanding, which we viewed as the episodes having ended. We included these episodes in our analysis because of the possibility of identifying phases of sensemaking and the role of scientific uncertainty as these episodes unfolded.

Next, to identify phases of sensemaking, we first reviewed literature about sensemaking (e.g., Ancona, 2012; Klein et al., 2006) and summarized key features of sensemaking. Then, based on this review, we inductively found similar patterns of how questions are raised; information pieces are gathered and synthesized in episodes. We identified and named phases of sensemaking based on the terms used in the literature.

The next step of analysis was to code uncertainties managed in the discussion and roles of scientific uncertainties as pedagogical resources. We first defined conceptual and epistemic uncertainty based on the existing literature (e.g., Chen, 2020; Lane & Maxfield, 2005). We then identified scientific uncertainties and types of the uncertainties based on the definitions of conceptual and epistemic uncertainty. Examples of conceptual and epistemic uncertainties that we coded in data are shown in Appendix 1. Next, we examined different roles of student scientific uncertainty as a pedagogical resource in sensemaking—specifically, we identified such roles based on how the resolution of the scientific uncertainties contributes to progressing the trajectory of sensemaking. Examples of the analysis are shown in Appendices 2 and 3. Then, we generated figures showing the trajectory of scientific uncertainty that were navigated through classroom discussion and pedagogical roles of scientific uncertainties that we identified. The three authors coded individually and then had meetings to match and revise codes that were initially different.

In the "Findings" section, we put representative episodes from different classrooms of the three phases identified through analysis. This was to (1) show different cases that we analyzed and (2) show representative episodes that clearly show our analysis results regarding all the roles of scientific uncertainties that we found in each phase.

Findings

Three phases of sensemaking were identified in the data. Table 2 shows an overview of the phases. In this section, we describe features of the three identified phases of sensemaking and the role of scientific uncertainties in each phase.

Phase 1: Focusing on a Driving Question Related to a Target Phenomenon

The first phase of sensemaking began with a teacher's provision of a target phenomenon. Presenting a scientific phenomenon, however, did not ensure students' successful engagement in sensemaking of the phenomenon. Students showed struggles to fully understand what the purpose of the phenomenon is and what features of the phenomenon they need to attend to. In Phase 1, it was thus important to support students to know what the problem is regarding the target phenomenon and come up with a driving question to answer. Conceptual and epistemic uncertainties took important pedagogical roles in this successful initial

Table 2 Overview of the three phases and the role of scientific uncertainty as pedagogical resource in sensemaking

Phase	Phase description	Pedagogical role of scientific uncertainties
Phase 1: focusing on a driving question related to a target phenomenon	A teacher's presentation of a target phenomenon and students' engagement in sensemaking	- Conceptual uncertainty: clarifying background conceptual knowledge and opening space to discuss and identify essential concepts related to a target phenomenon - Epistemic uncertainty: clarifying and reasoning the issue of a given problem and problematizing a target phenomenon
Phase 2: delving into multiple resources to develop plausible explanation(s)	Collecting multiple resources and developing initial ideas into plausible explanation(s)	- Conceptual uncertainty: clarifying students' initial ideas with the use of content knowledge and gathering data and information for development of new understanding - Epistemic uncertainty: connecting the collected data and information to develop a plausible explanation
Phase 3: examining the successfulness of the new understanding and concretizing it	Using the newly developed understanding to explain the problematized phenomenon, examining the fruitfulness of the new understanding	- Conceptual uncertainty: clarifying a connection between newly developed understanding in Phase 2 and the target phenomenon - Epistemic uncertainty: facilitating applications and synthesis of the newly developed understanding to make sense of the target phenomenon

engagement with the phenomenon. Conceptual uncertainty was leveraged as a resource to identify essential features to make sense of the phenomenon and retrieve and clarify related background conceptual knowledge. Epistemic uncertainty emerged intertwined with the conceptual uncertainty, prompting students to formulate a driving question that problematized the phenomenon in connection with the identified essential features.

We present an exemplary episode in Ms. Kim's biology classroom to show how students meaningfully engaged with a phenomenon and how student scientific uncertainty was managed and used as a pedagogical resource in this initial phase of sensemaking. This episode appeared in lessons where students were learning the effect of plant's transpiration on photosynthesis. Ms. Kim showed a video-recorded experiment in which students were required to anticipate the results—which plant between one whose leaves were waxed with Vaseline and the other not waxed would live longer (see Fig. 1)? Group discussions began after this introduction of the anchoring question. To answer this question, students first needed to understand the given phenomenon, specifically, what the initial conditions of the two plants in the experiment means. However, students' discussion in the beginning revealed their struggles in figuring out what the experiment condition means. We present an episode in one group of students—Jongmin's group as a representative example of such struggles. As experiencing difficulties in understanding the given phenomenon, Jongmin's group asked for help to Ms. Kim (see Table 3).

As shown in turns 684–691, students expressed their struggles in grasping what the target phenomenon is and asked for help. Subsequently, they faced an impasse of how to approach the problem and generate a claim. In other words, intertwined conceptual and epistemic uncertainties were evident in the beginning. Ms. Kim approached the group and provided supports by asking whether students understood what the given conditional information of the experiment means (turn 694). Then, she ensured that students knew what each information implied in the phenomenon by having several cycles of question-and-answer about necessary conceptual knowledge (e.g., plant transpiration through stoma; turns 690–727). Her questioning continued until students reached an understanding of the experiment setting. In this process, student uncertainties about

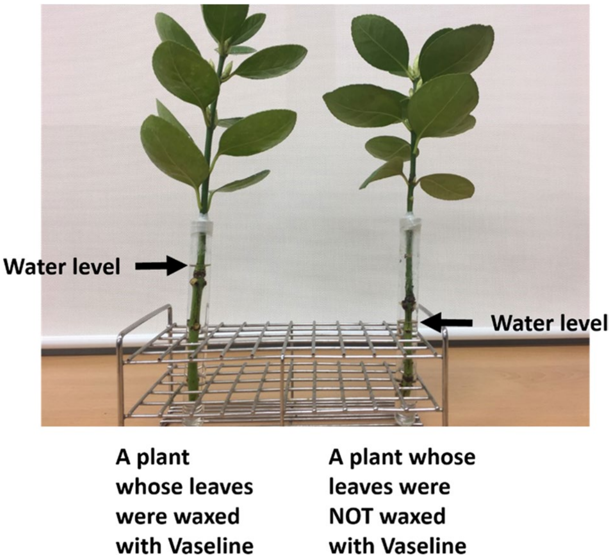

Fig. 1 A snapshot of video showing the experiment of comparing reduced water level of the tubes with two plants with/without Vaseline on their leaves

Table 3 Excerpt illustrating student struggles with and teacher supports for engaging with the given phenomenon

Turn	Speaker	Utterance	Type of scientific uncertainty as a pedagogical resource	Reason for the coding of scientific uncertainty as a pedagogical resource
684	Jongmin	(To Ms. Kim) I cannot figure this out.	Conceptual uncertainty about what the experiment conditions of the target phenomenon means	Jongmin's expression of conceptual uncertainty prompted Ms. Kim to assess what needed further clarification in order to initiate students' engagement with the phenomenon
685	Ms. Kim	Which part do you not understand?		
686	Jongmin	Everything.		
687	Minji	Haha.. (awkward smile)		
688	Ms. Kim	Then, do you understand what we are doing?		
689	Jongmin	Yes		
690	Ms. Kim	Okay, so you understand what we are doing. Then, what do you not understand? Do you understand the phenomenon?		
691	Jongmin	No		
692	Ms. Kim	Okay. There are two plants in the similar size. Do you see the leaves here? Leaves in one plant is left as it is, and another one was put Vaseline on. You know what Vaseline is, the lotion that is really sticky. So, the stoma on the leaves are blocked. Then, one plant is with stoma open, and another plant is blocked, right? Then, the plants are put in water. After a while, the water with the plant with no treatment was reduced. So what does the reduced water means?	Conceptual uncertainty about what the reduced water represents	Ms. Kim raised conceptual uncertainty by posing questions about the meaning of the given conditions which were essential for students' understanding of the target phenomenon
693	Jongmin	Good?		
694	Ms. Kim	What does it mean that water was reduced?		
695	Jongmin	That the plant took the water…		

Table 3 (continued)

Turn	Speaker	Utterance	Type of scientific uncertainty as a pedagogical resource	Reason for the coding of scientific uncertainty as a pedagogical resource
696	Ms. Kim	The plant took the water. Took and do what? How is it relevant to the leaves?	Conceptual uncertainty about the relation between absorbing water, implied by the reduced water, and transpiration	Ms. Kim maintained the conceptual uncertainty to support students to explain the relation between the water absorption and transpiration in the plant
…				
711	Ms. Kim	So, what does the reduced water mean? (to Jongmin) What went out through stoma when water is reduced?		
712	Jongmin	Air…		
713	Doyeon	Air… and photosynthesis… (pointing at the textbook)		
714	Ms. Kim	Right. Air. Because the plant absorbed water		
…				
722	Ms. Kim	But why do you think water on this side didn't reduce?	Conceptual uncertainty about why the water of the leaf waxed with Vaseline did not reduce	Ms. Kim raised conceptual uncertainty to support students to differentiate different experiment conditions and understand what the phenomenon is about
723	Jongmin	Because it can't conduct transpiration		
724	Ms. Kim	Why?		
725	Jongmin	Because there is Vaseline on it		
726	Ms. Kim	Yes, that's what this phenomenon is		
727	Jongmin	Oh		
…				
737	Jongmin	(What we need to do is) To predict how the plants would grow?	Epistemic uncertainty about what and how to discuss; predictions along with a claim and reasoning	Ms. Kim resolved epistemic uncertainty to help students understand a way of resolving the problem
738	Ms. Kim	Umm, yes. Choose the claim that you agree with and justify your claim		

Table 3 (continued)

Turn	Speaker	Utterance	Type of scientific uncertainty as a pedagogical resource	Reason for the coding of scientific uncertainty as a pedagogical resource
739	Minji	Do leaves conduct photosynthesis by transpiration?	Epistemic uncertainty about a possible reasoning to support a claim	Minji raised an epistemic uncertainty by posing a driving question in an attempt to develop a reasoning (turn 752) to support a claim, problematizing the phenomenon
740	Jongmin	Umm…		
741	Doyeon	Huh? Umm…		
…				
752	Minji	So, if the plant can't transpire, it will die		

content knowledge that were necessary to understand what the phenomenon means were raised, maintained, and resolved. Once conceptual uncertainties were resolved, students' epistemic uncertainty of how to approach the problem was specified in terms of what and how to discuss (i.e., generating predictions on how the plants would grow; turn 737) and subsequently came up with a driving question to answer (i.e., how does transpiration contribute to the plant's photosynthesis?; turn 739). In other words, students' uncertainty shifted toward epistemic understanding of how to develop a possible reasoning to choose a claim about anticipating what would happen in the given experimental situation. That is, students' epistemic uncertainty contributed to problematizing the phenomenon.

Role of Scientific Uncertainties as Pedagogical Resources in Phase 1

This episode shows a beginning phase of sensemaking where student uncertainties are addressed to support students' initial engagement with a target phenomenon. Figure 2 presents the trajectory of scientific uncertainty navigation and pedagogical roles of scientific uncertainties navigated in Phase 1. Initial conceptual and epistemic uncertainties were entangled together and impeded students' engagement with the phenomenon. Students neither understood what scientific knowledge the experiment conditions correspond to nor how to approach the problem to make sense of the phenomenon. To fully engage with the phenomenon, scientific uncertainties related to prerequisite conceptual understanding were first raised and resolved. As the conceptual uncertainties mostly concerned prerequisite knowledge, this type of uncertainty (e.g., plant absorbing waters—transpiration) needed to be managed first to understand the target phenomenon. Once conceptual uncertainties were addressed, epistemic uncertainties on how and what to focus on to answer the question were raised regarding how to generate knowledge (e.g., how to predict the plants would grow) and a driving question (e.g., "Do leaves conduct photosynthesis by transpiration?") to make progress in sensemaking afterward.

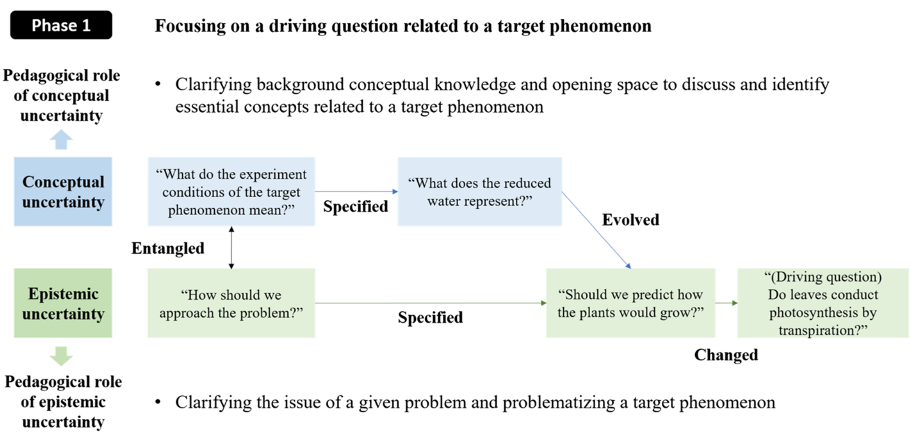

Fig. 2 The trajectory of scientific uncertainty navigation and pedagogical roles of scientific uncertainty navigated in Phase 1 in Ms. Kim's classroom

Phase 2: Delving into Multiple Resources to Develop Plausible Explanation(s)

The next phase following the elicitation of student ideas was an exploration of multiple resources to develop plausible explanations. This phase was characterized by epistemic uncertainties raised from student struggles to collect resources to evaluate and revise the initial ideas. In the process of managing the epistemic uncertainty, students navigated conceptual uncertainty to clarify their initial ideas and collect pieces of information as resources for subsequent development of new understanding.

These features were representatively shown in a science club activity organized by Ms. Hong in a Korean middle school. In this science club, students in groups were asked to make sense of ecological phenomena in the schoolyard. The core scientific concept in this classroom was the structure of ecosystem. The episode appeared in a group that investigated why four-leaf clovers were found frequently in the part near a roadway. The students formulated an initial hypothetical explanation that "(pollution of) the soil caused mutations of plants, causing the appearance of four leaves." After the formulation of the hypothesis, students engaged in a group discussion to collect data and information, wrestling with epistemic uncertainties of (1) how to translate initial ideas expressed in everyday terms to new understanding with use of content knowledge and (2) how to connect the collected data and information to develop a plausible explanation.

The first information they collected was about whether the clover's trait of four leaves is a genetically inherited trait. The students were trying to contrive explanations of why there were a lot of four-leaf clovers, identifying the four-leaf trait as a mutation (turn 399). Noticing this student idea, Ms. Hong approached to the group and asked the following: "Do you mean that the four-leaf trait is genetically inherited mutation or environmentally caused mutation?" (Table 4 turn 400). This question raised a content uncertainty regarding the cause of four-leaf mutation, supporting the students to clarify their initial idea that the four-leaf trait is a mutation. To answer Ms. Hong's question, the students searched on the internet. The students found an information that said "Even if we try to produce more four-leaf clovers by planting the existing ones, we cannot produce them because it is environmentally caused mutation." Based on this information, the students resolved their question regarding the cause of mutation, concluding that four-leaf trait can be "the mutation caused by environmental condition, not the trait determined by inherited genes" (turn 411). In this way, the students translated and clarified their initial idea by using content knowledge about genetic inheritance and mutation of clovers.

Then, Siwon raised another question to solve: "So, by saying mutation caused by an environmental condition, it would mean that there is something unusual in soil or water around the four-leaf clovers." Subsequently, he added, "Now we need to find out why the soil in this area is unusual." However, the students struggled to figure out what kind soil features to investigate and how to approach it. This struggle was shown from students' discussion, which reached a deadlock after saying, "Let's investigate the soil." and "We need to investigate features (of the soil) other than pH. Various features." This indicated an epistemic uncertainty regarding how to figure out uniqueness of the soil with abundant four-leaf clovers. The teacher supported students by specifying factors—phosphorous and nitric acids—that they can investigate to find out the uniqueness of soil. She provided reference online materials that introduce the two factors and tool kits to measure levels of phosphorous and nitric acids in soil. Namely, she supported

Table 4 Excerpt illustrating student exploration of resources to develop plausible explanations

Turn	Speaker	Utterance	Type of scientific uncertainty as a pedagogical resource	Reason for the coding of scientific uncertainty as a pedagogical resource
399	Taeri	So, it (the four-leaf trait) is a mutation	Conceptual uncertainty about the cause of four-leaf mutation	This conceptual uncertainty is used to support students clarify their ideas of how the pollution of soil caused appearance of four-leaf trait in clovers
400	Ms. Hong	Do you mean that the four-leaf trait is genetically inherited mutation or environmentally caused mutation?		
401	Siwon	It just says that the four-leaf trait is a mutation. Temporary mutation		
402	Ms. Hong	Okay. Then, what are specific examples of temporary mutation?		
…		(Students searching on the internet)		
411	Siwon	It says here that the mutation is caused by environmental condition, not the trait determined by inherited genes		

students to focus on and wrestle with a conceptual uncertainty of whether it is phosphorous acid level or nitric acid level of the soil that is unique and became a potential cause of more occurrences of four-leaf clovers. Using the materials and tool kits provided, the students found out higher nitric acid level of the soil on which more four-leaf clovers were found.

As the students found out that the nitric oxide and phosphoric oxide level is higher in the soil around four-leaf clovers, Siwon asked a question, “Hey, I guess nitric oxides are heavier than the air, right?” This utterance indicates a raise of another epistemic uncertainty of how to connect the collected data to develop a plausible explanation. In addition, this question indicates that Siwon found that nitric oxides are one of the main components of vehicle exhaust and that it can sink to the ground as emitted from the vehicle. That is, Siwon noticed that there is a road nearby the investigated area and managed a conceptual uncertainty of what kind of nitric oxide gas is in the vehicle exhaust. Siwon developed a new knowledge based on the collected data and information found on the internet, which is that nitric acids emitted from vehicles nearby came down to the soil and caused a mutation of clover, leading to the expression of four-leaf trait.

Role of Scientific Uncertainties as Pedagogical Resources in Phase 2

Figure 3 presents the trajectory of scientific uncertainty navigation and pedagogical role of scientific uncertainties in Phase 2. In this episode, scientific uncertainties emerged as students collect and use information pieces to develop a plausible explanation. Two roles of conceptual uncertainties were identified: clarifying students’ initial ideas and collecting data and information pieces to develop a plausible explanation. The first role was evident from Ms. Hong’s question facilitating students to clarify how they think “mutation” occurred. The second role of conceptual uncertainty was shown from supporting students to grasp what are specific measurements of the soil conditions to justify the uniqueness of it and what kind of nitric oxide gas is in the vehicle exhaust. With the resolution of this uncertainty, students were able to address the subsequent epistemic uncertainty of figuring out why the soil with more four-leaf clovers on it was unusual. Epistemic uncertainty was managed to connect the collected data to develop a plausible explanation of how the soil became unusual.

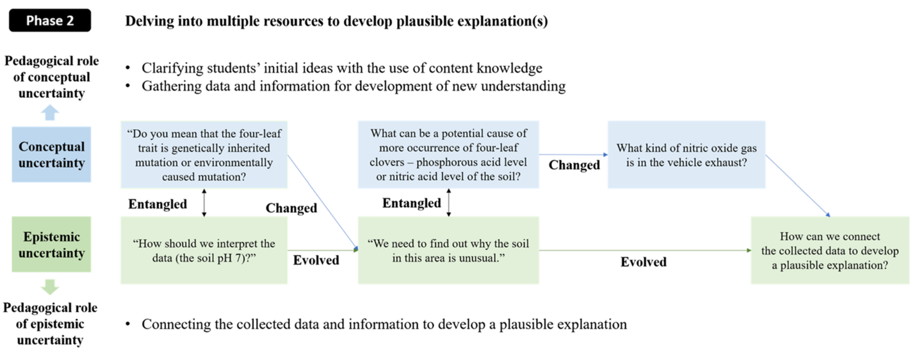

Fig. 3 The trajectory of scientific uncertainty navigation and pedagogical roles of scientific uncertainty navigated in Phase 2 in Ms. Hong’s classroom

Phase 3: Examining the Successfulness of the New Understanding and Concretizing It

Sensemaking cannot be done until students "organize to make sense of equivocal inputs and enact that sense back into the world to make it more orderly" (Brown et al., 2015, p. 267). Without enacting newly developed understanding back to the original problem, it is difficult to understand if the new knowledge is coherent, sufficient, and fruitful to solve the problem. In line with this literature, in the last phase, scientific uncertainty was used to help students evaluate successfulness of the newly learned knowledge by applying it to interpret the phenomenon problematized in Phase 1. Conceptual uncertainty was derived from students' struggle to connect new knowledge to explaining the target phenomenon. Epistemic uncertainty came from students' struggle of applying new knowledge to interpret the phenomenon and examining the coherence and successfulness of the new knowledge.

Ms. Jager's fifth-grade human respiratory system unit shows an exemplary episode of Phase 3. In her classroom, students built a simulation model to understand the dynamic movement of breathing and relationship between pressure and volume in chest cavity, using the materials such as plastic bottles, straws, and clay. However, Ms. Jager did not want the class to end with the completion of a simulation model building. She created a whole-class presentation task that required students to apply their understanding by using alternative modal representations, such as drawing, writing a storybook, and acting, to explain breathing process.

Flora's group decided to create a drawing of the chest cavity to explain their understanding of the movement of human breathing. Figure 4 captures some snapshots showing the process of how Flora and her group members (Lyndia & Jack) generated the drawing in front of the class. The drawing lasted for around 5 min. When Flora's

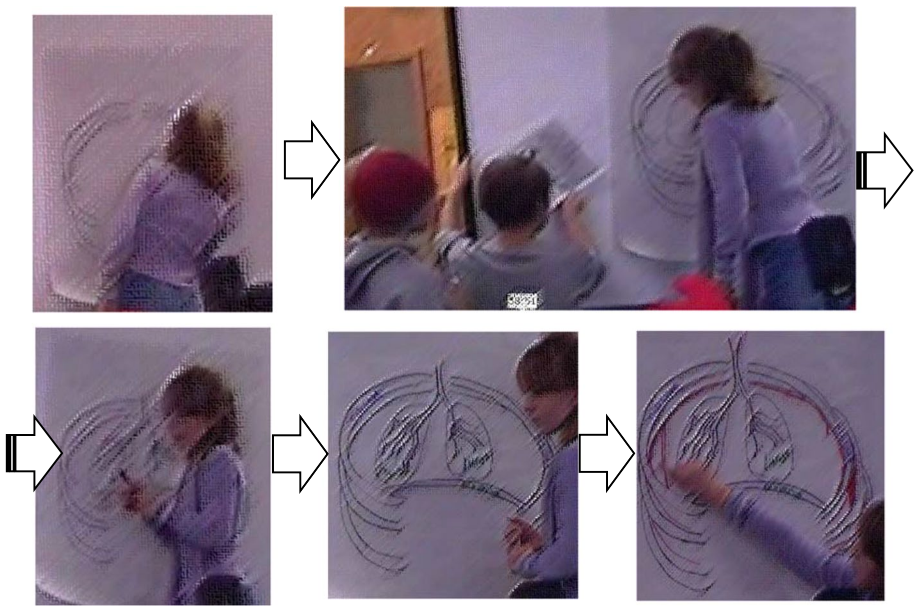

Fig. 4 A group of students creating a drawing of the chest cavity to explain their understanding of the movement of human breathing

group drew their idea on the board with explanation, Ms. Jager captured a student self-generated language—airtight box, and asked “You keep saying ‘airtight box,’ and everyone out here keeps saying ‘what are you talking about’.” The following excerpts in Table 5 show how Ms. Jager started from student self-generated language to shape the application of their understanding to explain the dynamic relationship between pressure and volume caused by the diaphragm.

The conversation shows that even though students have built a scientific correct model to represent respiratory system, they still struggled to make the connection between their everyday language and scientific language (Table 5, turns 73–76) and explain their understanding of the role of diaphragm on controlling the dynamic relationship between pressure and volume in chest cavity (turns 111–121). For example, Ms. Jager raised a conceptual uncertainty about the meaning of “airtight box” and made the connection it to scientific language “chest cavity.” Subsequently, Ms. Jager asked another question of why the chest cavity is important, raising another conceptual uncertainty about what the function of chest cavity is (turn 111). Jack answered to this question, indicating that the chest cavity is related to pressure that causes movement of the air (turn 112). By managing the two conceptual uncertainties, students were able to concretize what chest cavity means. Then, Ms. Jager raised an epistemic uncertainty that encouraged students to use their understanding of the chest cavity to explain breathing (turn 113). Ms. Jager’s raise of these uncertainties scaffolded students to apply and elaborate their understanding to explain how the movement of diaphragm results in the change of pressure and volume in chest cavity.

In the end of this episode, students reflected on how much their ideas changed from the beginning of the unit. For example, Maria said: “our ideas in the beginning were kinda crazy, like using the FAN for our models [class laughs], and as the air blowing in… they’re a LOT different from it now.” Lavender said: “Yeah, because now we know that it’s the diaphragm that causes it. I didn’t even know that we HAD a diaphragm before this.” This suggests that sensemaking is more than a “aha!” moment, but a prolonged process by including student uncertainty as a resource to build their understanding toward a problematized phenomenon.

Role of Scientific Uncertainties as Pedagogical Resources in Phase 3

This episode shows that Ms. Jager continuously raised different scientific uncertainties to support students to construct more coherent knowledge toward the explanation of human breathing process. Figure 5 presents the trajectory of scientific uncertainty navigation and pedagogical role of scientific uncertainties in Phase 3. Conceptual uncertainties were navigated to build the connection between newly developed understanding in Phase 2 and explaining the target phenomenon. This was shown from Ms. Jager’s questions “WHAT is the chest cavity?” and “why is THAT [chest cavity] important?” Once students responded to the uncertainty, their peers focused on helping Flora’s group to elaborate and apply their understanding to explain the movement of respiratory system, that shift to epistemic-focus. Here, epistemic uncertainty followed, facilitating students to apply their simulation model to explain the target phenomenon, evaluating the successfulness of their model. As such, scientific uncertainties in Phase 3 were used to support students to enact their new understanding in Phase 2 to explain the problematized phenomenon.

Table 5 Excerpt illustrating student explanation of their understanding of the dynamic relationship between pressure and volume in chest cavity

Turns	Speaker	Utterance	Type of scientific uncertainty as a pedagogical resource	Reason for the coding of scientific uncertainty as a pedagogical resource
73	Henry	It's, it says "the top sides of the chest cavity are formed by the ribs and attached muscles, and the bottom by a large muscle called the diaphragm."		
74	Green	So part of the, chest cav-…?		
75	Ms. Jager	WHAT is the chest cavity?	Conceptual uncertainty about what the chest cavity means	Ms. Jager raised a conceptual uncertainty to clarify meaning of the term that students used and use it in their conversation
76	Noah	Would you, like, DRAW where it is? Cuz like, I still don't understand one hundred percent. So if you could like draw it up there		
…				
111	Ms. Jager	Now why is THAT important?	Conceptual uncertainty about what the function of chest cavity is	Ms. Jager raised a conceptual uncertainty to support students use their understanding to explain the function of chest cavity
112	Jack	Cuz there'll be pressure to…		
113	Ms. Jager	So what does pressure have to do, with breathing? (refer to their drawing)	Epistemic uncertainty about how to elaborate and apply new understanding to explain the target phenomenon	Ms. Jager raised an epistemic uncertainty prompting students to elaborate their understanding of function of chest cavity and apply their new understanding to explain the target phenomenon
114	Lydia	If there isn't enough pressure then the diaphragm, if it moves up then the lungs can't deflate as easy, cuz you need, um, enough room to, um, inflate again		
115	Flora	When the… the pressure in the chest cavity reduces when the, the diaphragm lets itself down, because when your diaphragm, when the diaphragm pushes itself up, there's less space and more pressure, and then when the diaphragm lets down, there's more space and less pressure		

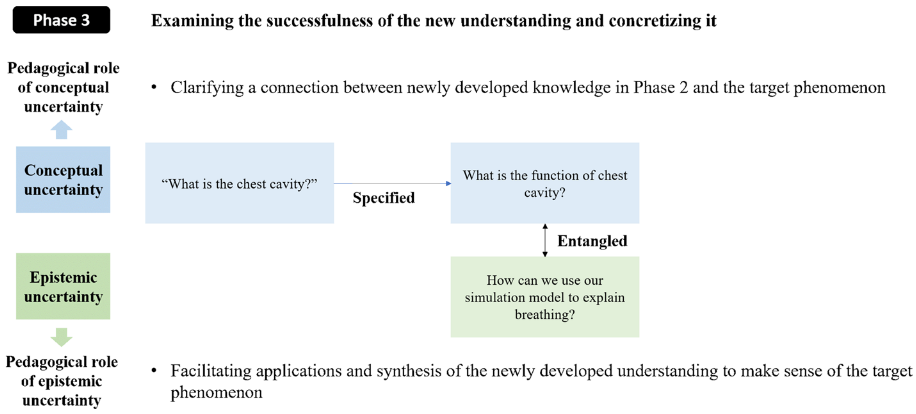

Fig. 5 The trajectory of scientific uncertainty navigation and pedagogical roles of scientific uncertainty navigated in Phase 3 in Ms. Jager's classroom

Conclusion and Discussion

The Trajectory of Sensemaking that Includes Distinctive Phases

The current study identified three essential phases of sensemaking that develop with student uncertainty in the science classroom. This finding indicates potential of using student scientific uncertainty to develop prolonged trajectory of sensemaking. Sensemaking has been often treated as instant moments where teachers feed information to students (Gooding & Metz, 2011). However, as shown in this study's findings, we find that sensemaking is a process with distinctive phases to grasp better understanding. Specifically, as in Phase 1, students' engagement in sensemaking discussion did not occur immediately after the teacher's introduction of the phenomenon. The teacher supported students to clarify background knowledge by managing their conceptual uncertainty and problematize a given phenomenon by raising epistemic uncertainty. After then, in Phase 2, students' exploration of multiple resources for development of plausible explanations followed. In this phase, conceptual uncertainty was used as a pedagogical resource to clarify students' initial ideas and gather information, which were used to resolve the epistemic uncertainty regarding developing plausible explanations. There was another phase, Phase 3, where students evaluated the successfulness of their new understanding by applying it to explain the problematized phenomenon. The teacher utilized both conceptual uncertainty and epistemic uncertainty in this phase, too: conceptual uncertainty to clarify the connection between students' newly developed understanding and the target phenomenon and epistemic uncertainty to apply the new understanding to make sense of the problematized phenomenon.

This finding indicates that students' sensemaking of phenomena in the science classroom does not progress rapidly nor phases shifting radically. This finding is in line with the perspective on students' conceptual change as a gradual process, not a radical shift that can occur when a certain condition is achieved (Treagust & Duit, 2008). The three phases reflect the feature of sensemaking as identifying and resolving the gap of students' existing understanding to develop a better understanding (Cannady et al., 2019; Odden & Russ, 2019). In addition, this study's finding suggests students' scientific uncertainty to be potential pedagogical resources to develop the trajectory of sensemaking. The existing studies (e.g., Chen et al., 2019) have explored student scientific uncertainty in a generalized manner. This study delves deeper, identifying how roles of student uncertainty can vary across distinct phases of sensemaking, shedding light on the nuanced differences in these phases. Specifically, the findings of this study indicate that Phase 1 in sensemaking can be organized by addressing conceptual uncertainty in students' background knowledge and concretizing students' epistemic uncertainty of a target phenomenon. Phase 2 can progress by managing students' epistemic uncertainty of how to develop a plausible explanation. Conceptual uncertainty can be used to clarify student initial ideas and gather information pieces to use in subsequent development of new explanations. Phase 3 can be developed by addressing intertwined conceptual and epistemic uncertainties appearing in students' application of and reflection on their newly developed understandings in explaining a given phenomenon. Previous studies (Jordan and McDaniel, 2014; Star, 1985) emphasized scientific uncertainty as an impetus for knowledge development in scientific endeavor. Our finding is in line with these studies and is expected to support students to engage in sensemaking that reflects such feature of uncertainty in scientific endeavor.

The phases of sensemaking identified in this study can work as a framework of sensemaking that science teachers can refer to in designing sensemaking activities. Especially, the identification of sensemaking phases upon student uncertainty supports designing lessons with consideration of students' diverse explorations of phenomena and continuous development of sensemaking. For example, when attempting to support students to engage in sensemaking of a phenomenon, a teacher can anticipate that scientific uncertainties regarding background knowledge might be raised and use the uncertainties for students to problematize the target phenomenon. Furthermore, the distinguishing features of three phases indicate that teaching strategies need to be differentiated to support students' engagement in sensemaking. For example, in Phase 2, the teacher can use student conceptual uncertainties so that students can explore multiple resources for development of plausible explanations. Meanwhile, Phase 3 was about enacting the new understanding to explain the problematized phenomenon. Possible teaching strategy in Phase 3 can be to identify epistemic uncertainty regarding how to apply the new understanding to explain the phenomenon.

This study has identified three key phases of sensemaking, although it is possible that more specific phases could be discerned by taking a more microscopic view. For example, "Phase 1: Focusing on a Driving Question Related to a Target Phenomenon" can be untangled into students' initial grasp of a driving question and identification of gaps in their existing understanding. Further investigations into sensemaking to distinguish more phases could support teachers in implementing sensemaking within their science classrooms.

Epistemic Uncertainty and Conceptual Uncertainty Interweaved Together

With the emphasis on epistemic practices, epistemic uncertainty has been addressed more in science education (e.g., Chen & Techawitthayachinda, 2021). However, the process of sensemaking cannot be developed solely with epistemic uncertainty, and both epistemic and conceptual uncertainties play critical roles in building the trajectory of sensemaking. For example, in Phase 1, the management of conceptual uncertainty facilitated students' raise of epistemic uncertainty regarding how to approach and explain a target phenomenon. In Phase 2, conceptual uncertainty was navigated in the process of gathering resources to resolve epistemic uncertainties of how to resolve gaps in students' initial ideas. In Phase 3, conceptual uncertainty developed into an epistemic uncertainty of applying the knowledge to explain a target phenomenon.

As discussed in previous studies on uncertainties in sensemaking (Chen, 2022), epistemic uncertainties were important for students to engage in sensemaking of a target phenomenon, identify the gap in initial ideas to develop them further, and apply a developed knowledge to explain the phenomenon. The interweaved feature of epistemic and conceptual uncertainties indicates that attention to both types of uncertainty is needed to develop the trajectory of sensemaking that is coherent with students' view. Managing conceptual uncertainty helps clarify epistemic uncertainty regarding how to develop a new knowledge. Also, conceptual uncertainty of an explanation of phenomenon is what propels students' construction of new understanding in sensemaking while preceding epistemic uncertainties are maintained and/or resolved, or as new ones emerge.

In addition, the connection between epistemic uncertainty and conceptual uncertainty varied in each phase, which indicates different instructional strategies are needed to support students' management of scientific uncertainties in each phase. For example, in Phase 1, it would be necessary to support students to identify conceptual uncertainties and provide resources to resolve them so that students have necessary knowledge to engage in sensemaking. In Phase 2, teacher support on raising epistemic uncertainty regarding how to translate student initial ideas to new understanding with use of content knowledge can prompt students to engage in further management of conceptual uncertainties to collect information pieces for development and evaluation of their ideas. Future studies that develop such instructional strategies for each phase of sensemaking are needed to facilitate the enactment of sensemaking in the science classroom.

Limitation and Future Directions

This study examined how the process of sensemaking can develop with the navigation of student scientific uncertainty. While this study identified scientific uncertainty that emerged from student group discussion, it was limited in closely examining how individual students' scientific uncertainties are shared with other group members. Further research addressing this issue is needed to understand how individuals' scientific uncertainties become a community's uncertainty that is shared and resolved through group efforts. Another potential area for future research involves exploring other types of scientific uncertainty. While this study focused on conceptual and epistemic uncertainties, there can be other types of uncertainty, such as relational uncertainty (Jordan and McDaniel, 2014). Students' discursive interactions and idea development can be influenced by social relationships and emotional dynamics among the students (Finkelstein et al., 2019), which indicates that relational uncertainty could be another potential type of scientific uncertainty that students are navigating in sensemaking. We expect this line of study to contribute to understanding the process of how collective epistemic agency for sensemaking is developed in the science classroom.

Appendix 1 Codebook of types of scientific uncertainty

Table 6 Codebook of types of scientific uncertainty

Type of scientific uncertainty	Definition	Example
Content uncertainty	Students' subjective experience of being unsure or struggling about using existing content knowledge to understand a phenomenon	[Core concept: *Transpiration*] • Identified content uncertainty: What does the reduced water means? Ms. Kim: Okay, so you understand what we are doing. Then, what do you not understand? Do you understand the phenomenon? Jongmin: No Ms. Kim: Okay. There are two plants in the similar size. Do you see the leaves here? Leaves in one plant is left as it is, and another one was put Vaseline on. You know what Vaseline is, the lotion that is really sticky. So, the stoma on the leaves are blocked. Then, one plant is with stoma open, and another plant is blocked, right? Then, the plants are put in water. After a while, the water with the plant with no treatment was reduced. So *what does the reduced water means?* Jongmin: Good? Ms. Kim: What does it mean that water was reduced? [Core concept: *Ecosystem*] • Identified content uncertainty: Is the mutation of clover's leaf-number trait caused by environmental condition? Taeri: So, it (the four-leaf trait) is a mutation Ms. Hong: *Do you mean that the four-leaf trait is genetically inherited mutation or environmentally caused mutation?* Siwon: It just says that the four-leaf trait is a mutation. Temporary mutation Ms. Hong: So, which one is it, then? (Students searching on the internet)

Table 6 (continued)

Type of scientific uncertainty	Definition	Example
Epistemic uncertainty	Students' being unsure or struggling about generating new ideas by using existing epistemic knowledge	[Core concept: *Transpiration*] • Identified epistemic uncertainty: Do leaves conduct photosynthesis by doing transpiration? Ms. Kim: So, we can think in two ways. First, you can think that the plant is keeping water in it when the Vaseline is on, because it cannot transpire. So, it can grow well. That's the first claim. Another claim is that the plant without Vaseline on can grow better. What you need to do is. (…) Jongmin: Predict how the plants would grow? Ms. Kim: Umm, yes. Choose the claim that you agree with and justify your claim Minji: *Do leaves conduct photosynthesis by doing transpiration?* Jongmin: Umm… Doyeon: Huh? Umm… [Core concept: *Respiratory system*] • Identified epistemic uncertainty: What does pressure have to do with breathing? Henry: It's, it says "the top sides of the chest cavity are formed by the ribs and attached muscles, and the bottom by a large muscle called the diaphragm." (…) Ms. Jager: Now why is THAT important? Jack: Cuz there'll be pressure to… Ms. Jager: *So what does pressure have to do, with breathing?*

Appendix 2 Pedagogical role of student scientific uncertainty — content uncertainty

Table 7 Pedagogical role of student scientific uncertainty—content uncertainty

Pedagogical role of scientific uncertainty	Definition	Phase	Example
Clarifying background conceptual knowledge and opening space to discuss and identify essential concepts related to a target phenomenon	Developing a shared clear understanding of background knowledge and use the knowledge to understand what a target phenomenon is	Phase 1	[Core concept: *Transpiration*] Ms. Kim: Okay. There are two plants in the similar size. Do you see the leaves here? Leaves in one plant is left as it is, and another one was put Vaseline on. You know what Vaseline is, the lotion that is really sticky. So, the stoma on the leaves are blocked. Then, one plant is with stoma open, and another plant is blocked, right? Then, the plants are put in water. After a while, the water with the plant with no treatment was reduced. So *what does the reduced water means?* Jongmin: Good? Ms. Kim: What does it mean that water was reduced? Jongmin: That the plant took the water… Ms. Kim: The plant took the water. Took and do what? How is it relevant to the leaves? (…) Ms. Kim: So, what does the reduced water mean? (to Jongmin) What went out through stoma when water is reduced? Jongmin: Air… Doyeon: Air… and photosynthesis… (…) Jongmin: So it excretes water? Ms. Kim: Umm, water is converted to vapor, and the vapor goes out through stoma. You know that vapor is gas, right? So, when gases come and go through stoma, vapor also goes through stoma. That's what transpiration is. Now, this plant is actively conducting transpiration, right?

Table 7 (continued)

Pedagogical role of scientific uncertainty	Definition	Phase	Example
Clarifying students' initial ideas with the use of content knowledge	Searching and using content knowledge to concretize and develop students' initial ideas	Phase 2	[Core concept: *Ecosystem*] Taeri: So, it (the four-leaf trait) is a mutation Ms. Hong: *Do you mean that the four-leaf trait is genetically inherited mutation or environmentally caused mutation?* Siwon: It just says that the four-leaf trait is a mutation. Temporary mutation Ms. Hong: So, which one is it, then? (Students searching on the internet) Siwon: It says here that the mutation is caused by environmental condition, not the trait determined by inherited genes
Gathering data and information for development of new knowledge	Generating data and searching for information to use for developing understandings with an usage of scientific concepts	Phase 2	[Core concept: *Ecosystem*] Siwon: Now we need to find out why the soil in this area was unusual (…) Taeri: I think we need to discuss what features of the soil to analyze. So we can arrange necessary supplies [inaudible] (…) Taeri: We can measure pH. There are many features that we can measure. pH, and humidity of the soil, and… (…) nitric oxide level (…) (Students measure pH, humidity, and nitric oxide level of the soil where four-leaf clovers were highly distributed.)
Clarifying a connection between newly developed understanding in Phase 2 and the target phenomenon	Eliciting students' concretized ideas of their explanation of understanding newly developed in Phase 2 to apply the understanding in explaining the target phenomenon	Phase 3	[Core concept: *Respiratory system*] Henry: It's, it says "the top sides of the chest cavity are formed by the ribs and attached muscles, and the bottom by a large muscle called the diaphragm." Green: So part of the, chest cav-…? Ms. Jager: WHAT is the chest cavity? Noah: Would you, like, DRAW where it is? Cuz like, I still don't understand one hundred percent. So if you could like draw it up there

Appendix 3 Pedagogical role of student scientific uncertainty — epistemic uncertainty

Table 8 Pedagogical role of student scientific uncertainty—epistemic uncertainty

Ways that student scientific uncertainty is used as a pedagogical resource	Definition	Phase	Example
Clarifying the issue of a given problem and problematizing a target phenomenon	Eliciting student initial ideas and raising questions that support students to notice incoherence in their ideas and figure out how to approach a driving question and generate a claim	Phase 1	[Core concept: *Transpiration*] Ms. Kim: So, we can think in two ways. First, you can think that the plant is keeping water in it when the Vaseline is on, because it cannot transpire. So, it can grow well. That's the first claim. Another claim is that the plant without Vaseline on can grow better. What you need to do is. (…) Jongmin: Predict how the plants would grow? Ms. Kim: Umm, yes. Choose the claim that you agree with and justify your claim Minji: *Do leaves conduct photosynthesis by doing transpiration?* Jongmin: Umm… Doyeon: Huh? Umm…

Table 8 (continued)

Ways that student scientific uncertainty is used as a pedagogical resource	Definition	Phase	Example
Connecting the collected data and information to develop a plausible explanation	Using collected data and information as evidence to generate, justify, and evaluate a plausible explanation	Phase 2	[Core concept: *Ecosystem*] Siwon: We need to check if there was nitric oxide found in the soil… (…) Siwon: Hey, I guess nitric oxides are heavier than the air, right? Minchan: Umm… Heavier than the air? (…) Siwon: I'm asking this question because, we found many four-leaf clovers nearby the road. So, I thought, nitric oxides exhausted from vehicles could go down to the ground and affect the soil Taeri: You mean nitric oxides in the vehicle exhaust? Siwon: (Reading an information found on the internet) "The analysis results reveal that main components of vehicle exhaust are carbon monoxide, carbon dioxide, nitric oxides, hydrocarbons, oxygen, and particulate matters." I think harmful gases among these components are monoxide, hydrocarbons, nitric oxides, and particulate matters

Table 8 (continued)

Ways that student scientific uncertainty is used as a pedagogical resource	Definition	Phase	Example
Facilitating applications and synthesis of the newly developed understanding to explain the target phenomenon	Using the newly developed understanding to interpret the target phenomenon and examine the coherence and fruitfulness of the new understanding	Phase 3	[Core concept: *Respiratory system*] Henry: It's, it says "the top sides of the chest cavity are formed by the ribs and attached muscles, and the bottom by a large muscle called the diaphragm." (…) Ms. Jager: Now why is THAT important? Jack: Cuz there'll be pressure to… Ms. Jager: *So what does pressure have to do, with breathing?* Lydia: If there isn't enough pressure then the diaphragm, if it moves up then the lungs can't deflate as easy, cuz you need, um, enough room to, um, inflate again Flora: When the… the pressure in the chest cavity reduces when the, the diaphragm lets itself down, because when your diaphragm, when the diaphragm pushes itself up, there's less space and more pressure, and then when the diaphragm lets down, there's more space and less pressure

Acknowledgements This research was funded by the National Science Foundation (Award # 2100879) to explore teachers' capacity to manage student epistemic uncertainty to support student's productive struggle and the development of conceptual understanding during project-based learning instruction. The opinions expressed herein are our own and not necessarily those of the National Science Foundation.This work was supported by the Ministry of Education of the Republic of Korea and the National Research Foundation of Korea (NRF-2020S1A5B5A16083113).

Declarations

Conflict of Interest The authors declare no competing interests.

References

Ancona, D. (2012). Sensemaking: Framing and acting in the unknown. In S. Snook, N. Nohria, & R. Khurana (Eds.), *The handbook for teaching leadership: Knowing, doing, and being* (pp. 3–21). Sage Publications.

Beven, K. (2016). Facets of uncertainty: Epistemic uncertainty, non-stationarity, likelihood, hypothesis testing, and communication. *Hydrological Sciences Journal, 61*(8), 1652–1665.

Brown, A. D., Colville, I., & Pye, A. (2015). Making sense of sensemaking in organization studies. *Organization Studies, 36*(2), 265–277.

Cannady, M. A., Vincent-Ruz, P., Chung, J. M., & Schunn, C. D. (2019). Scientific sensemaking supports science content learning across disciplines and instructional contexts. *Contemporary Educational Psychology, 59*, 101802.

Chakravartty, A. (2017). Knowledge under ontological uncertainty. In A. Chakravartty (Ed.), *Scientific ontology: Integrating naturalized metaphysics and voluntarist epistemology* (pp. 167–200). Oxford University Press.

Chen, Y. -C. (2020). Dialogic pathways to manage uncertainty for productive engagement in scientific argumentation. *Science & Education, 29*, 331–375.

Chen, Y. -C. (2022). Epistemic uncertainty and the support of productive struggle during scientific modeling for knowldge co-development. *Journal of Research in Science Teaching*. *59*(3), 383–422.

Chen, Y. -C., & Qiao, X. (2020). Using students' epistemic uncertainty as a pedagogical resource to develop knowledge in argumentation. *International Journal of Science Education, 42*(13), 2145–2180.

Chen, Y. -C., Benus, M. J., & Hernandez, J. (2019). Managing uncertainty in scientific argumentation. *Science Education, 103*(5), 1235–1276.

Chen, Y. -C., & Techawitthayachinda, R. (2021). Developing deep learning in science classrooms: Tactics to manage epistemic uncertainty during whole-class discussion. *Journal of Research in Science Teaching, 58*(8), 1083–1116.

Cho, H., Ha, H., & Kim, H. -B. (2019). Exploring the role of collaborative reflection in small group argumentation: Focus on students' epistemic considerations and practices. *Journal of the Korean Association for Science Education, 39*(1), 1–12.

Conlin, L. D. (2013). *Three views of an Aha! moment: Comparing tutorial groups' affective responses to a moment of sudden conceptual insight*. Poster Presentation at 2013 Physics Education Research Conference. Portland, OR.

Engle, R. A., & Conant, F. R. (2002). Guiding principles for fostering productive disciplinary engagement: Explaining an emergent argument in a community of learners classroom. *Cognition and Instruction, 20*(4), 399–483.

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.

Flood, V. J., Amar, F. G., Nemirovsky, R., Harrer, B. W., Bruce, M. R. M., & Wittmann, M. C. (2015). Paying attention to gesture when students talk chemistry: Interactional resources for responsive teaching. *Journal of Chemical Education, 92*(1), 11–22.

Ford, M. J., & Wargo, B. M. (2012). Dialogic framing of scientific content for conceptual and epistemic understanding. *Science Education, 96*(3), 369–391.

Furberg, A., & Silseth, K. (2022). Invoking student resources in whole-class conversations in science education: A sociocultural perspective. *Journal of the Learning Sciences, 31*(2), 278–316.

Gooding, J., & Metz, B. (2011). From misconceptions to conceptual change. *The Science Teacher, 78*(4), 34–37.

Ha, H., & Choi, Y. (2023). Supporting students' use of ecological concepts in field-based modeling of ecological phenomena. *International Journal of Science and Mathematics Education, 21*, 2215–2235.

Haverly, C., Barton, A. C., Schwarz, C. V., & Braaten, M. (2020). "Making space": How novice teachers create opportunities for equitable sense-making in elementary science. *Journal of Teacher Education, 71*(1), 63–79.

Jordan, M. E., & McDaniel, R. R., Jr. (2014). Managing uncertainty during collaborative problem solving in elementary school teams: The role of peer influence in robotics engineering activity. *The Journal of the Learning Sciences, 23*, 490–536.

Kampourakis, K. (2018). Science and uncertainty. *Science & Education, 27*, 829–830.

Kampourakis, K., & McCain, K. (2020). *Uncertainty: How it makes science advance*. Oxford University Press.

Kirch, S. A. (2009). Identifying and resolving uncertainty as a mediated action in science: A comparative analysis of the cultural tools used by scientists and elementary science students at work. *Science Education, 94*(2), 308–335.

Klein, G., Moon, B., & Hoffman, R. R. (2006). Making sense of sensemaking 1: Alternative perspectives. *IEEE Intelligent Systems, 21*(4), 70–73.

Lane, D. A., & Maxfield, R. R. (2005). Ontological uncertainty and innovation. *Journal of Evolutionary Economics, 15*, 3–50.

Lowell, B. R., & Cherbow, K., & McNeill, K. L. (2022). Considering discussion types to support collective sensemaking during a storyline unit. *Journal of Research in Science Teaching, 59*(2), 195–222.

Manz, E. (2015). Resistance and the development of scientific practice: Designing the mangle into science instruction. *Cognition and Instruction, 33*(2), 89–124.

Manz, E. (2018). Designing for and analyzing productive uncertainty in science investigations. In J. Kay & R. Luckin (Eds.), *Rethinking learning in the digital age: Making the learning sciences count, 13th International Conference of the Learning Sciences (ICLS) 2018, Volume 1*. International Society of the Learning Sciences.

Manz, E., & Suárez, E. (2018). Supporting teachers to negotiate uncertainty for science, students, and teaching. *Science Education, 102*(4), 771–795.

Mercer, N., & Littleton, K. (2007). *Dialogue and the development of children's thinking: A sociocultural approach*. Routledge.

Merriam, S. B. (1998). *Qualitative research and case study applications in education: Revised and expanded from case study research in education*. Jossey-Bass.

Metz, K. E. (2004). Children's understanding of scientific inquiry: Their conceptualization of uncertainty in investigations of their own design. *Cognition and instruction, 22*(2), 219–290.

National Research Council [NRC] (2012). *A framework for K-12 science education: Practices, crosscutting concepts, and core ideas*. National Academies Press.

Naumer, C. M., Fisher, K. E., & Dervin, B. (2008). Sense-making: A methodological perspective. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Vol. 8, pp. 506–513). Florence, Italy: SIGCHI.

Odden, T. O. B., & Russ, R. S. (2019). Defining sensemaking: Bringing clarity to a fragmented theoretical construct. *Science Education, 103*, 187–205.

Organisation for Economic Co-operation and Development [OECD] (2019). *PISA 2018 assessment and analytical framework*. OECD.

Osborne, J. (2014). Teaching scientific practices: Meeting the challenge of change. *Journal of Science Teacher Education, 25*, 177–196.

Rapkiewcz, J., Park, J., Chen, Y. -C., & Jordan, M. E. (2023). Student uncertainty as a pedagogical resource [SUPeR]: Using the SUPeR approach to investigate electromagnetic force. *Science Scope, 46*(7), 24–31.

Reiser, B. J., Novak, M., & McGill, T. A. W. (2017). *Coherence from the students' perspective: Why the vision of the framework for K-12 science requires more than simply "combining" three dimensions of science learning*. Paper prepared for the Board on Science Education Workshop "Instructional Materials for the Next Generation Science Standards."

Reiser, B. J., Novak, M., McGill, T. A. W., & Penuel, W. R. (2021). Storyline units: An instructional model to support coherence from the students' perspective. *Journal of Science Teacher Education, 32*(7), 805–829.

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.

Schwarz, C. V., Passmore, C., & Reiser, B. J. (2017). *Helping students make sense of the world: Next generation science and engineering practices*. NSTA Press.

Scott, P. H., Mortimer, E. F., & Aguiar, O. G. (2006). The tension between authoritative and dialogic discourse: A fundamental characteristic of meaning making interactions in high school science lessons. *Science Education, 90*(4), 605–631.

Sensevy, G. (2014). Characterizing teaching effectiveness in the joint action theory in didactics: An exploratory study in primary school. *Journal of Curriculum Studies, 46*(5), 577–610.

Sikorski, T.-R., & Hammer, D. (2017). Looking for coherence in science curriculum. *Science Education, 101*, 929–943.

Star, S. L. (1985). Scientific work and uncertainty. *Social Studies of Science, 15*(3), 391–427.

Tekkumru-Kisa, M., Stein, M. K., & Doyle, W. (2020). Theory and research on tasks revisited: Task as a context for students' thinking in the era of ambitious reforms in mathematics and science. *Educational Researcher, 49*(8), 606–617.

Treagust, D. F., & Duit, R. (2008). Conceptual change: A discussion of theretical, methodological and practical challenges for science education. *Cultural Studies of Science Education, 3*, 297–328.

Warren, B., Ballenger, C., Ogonowski, M., Rosebery, A. S., & Hudicourt-Barnes, J. (2001). Rethinking diversity in learning science: The logic of everyday sense-making. *Journal of Research in Science Teaching, 38*(5), 529–552.

Watkins, J., & Manz, E. (2022). Characterizing pedagogical decision points in sense-making conversations motivated by scientific uncertainty. *Science Education, 106*(6), 1408–1441.

Watkins, J., Hammer, D., Radoff, J., Jaber, L. Z., & Phillips, A. M. (2018). Positioning as not-understanding: The value of showing uncertainty for engaging in science. *Journal of Research in Science Teaching, 55*(4), 573–599.