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Undergraduate chemistry students' sensemaking in a laboratory setting: the interplay of knowledge gaps and epistemic emotions

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This study investigates how undergraduate chemistry students engage in sensemaking during an inquiry-based Boyle's law laboratory activity, focusing on how different types of knowledge gaps and associated epistemic emotions guide their sensemaking trajectories. A holistic multiple-case study design was employed, with sensemaking episodes serving as the unit of analysis. Two student groups were purposefully selected to represent contrasting sensemaking trajectories. Group 1 exhibited a sustained sensemaking trajectory and completed the activity, whereas Group 2 exhibited a disengaging sensemaking trajectory and ultimately withdrew from the task without arriving at a coherent resolution. Data were collected through audio and video recordings, activity sheets, and epistemic emotion diaries, and were analyzed thematically. The results revealed clear differences between the groups. Group 1 primarily encountered procedural knowledge gaps. These gaps involved relatively low element interactivity and were resolved through collaborative reasoning. By contrast, Group 2 encountered conceptual and epistemic gaps that required the coordination of multiple abstract constructs, imposed high cognitive demands, and remained unresolved. Epistemic emotions also diverged markedly across the two groups. Both began the activity with curiosity and surprise, yet Group 1 sustained positive emotions that helped them manage confusion productively. Group 2 experienced increasing frustration and boredom, reflecting a trajectory of hopeless confusion that hindered sustained sensemaking. The interaction of unresolved gaps and negative epistemic emotions seemed to be associated with Group 2's disengagement. The findings suggest the instructional relevance of attending to both cognitive demands and epistemic emotions, particularly in moments when students encounter persistent knowledge gaps during laboratory sensemaking.

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Introduction

While sensemaking is central to science learning, ambiguities persist regarding its definition and underlying mechanisms (Odden and Russ, 2019a; Ha *et al.*, 2024a, 2024b). Sensemaking involves actively resolving perceived gaps or inconsistencies in one's understanding by constructing or revising explanations (Odden and Russ, 2019a). It includes behaviors such as connecting scientific ideas to real-world contexts, coordinating representations, evaluating the plausibility of solutions, and reframing problems as coherent phenomena (Chen *et al.*, 2013). Sensemaking supports deep understanding (Ford, 2012; Danielak *et al.*, 2014), facilitates knowledge transfer to novel contexts (Kapon and diSessa, 2012), and aligns instruction with authentic disciplinary practices, which in turn fosters more meaningful and engaging learning (Ford, 2012; NSTA, 2024).

This study adopts Odden and Russ's (2019a) definition of sensemaking and their epistemic game framework (2018), which outlines four stages: activating prior knowledge, recognizing a gap, generating explanatory ideas, and working toward a resolution. Within this framework, "vexing questions" indicate gaps that trigger inquiry (Odden and Russ, 2019b). Importantly, not all gaps pose the same cognitive demands on students (De Jong and Ferguson-Hessler, 1996; McCormick, 1997).

Sensemaking is also driven by epistemic emotions (Pekrun, 2021; Pekrun *et al.*, 2023; Vilhunen *et al.*, 2023), which can act as both catalysts and constraints (D'Mello and Graesser, 2012; Arguel *et al.*, 2019). The trajectory of these emotions over time determines whether learners persist in inquiry or withdraw from it (Vogl *et al.*, 2020; Criswell *et al.*, 2025).

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In the present study, sensemaking is conceptualized as a process influenced by the interplay of knowledge gaps and epistemic emotions as students work to make sense of experimental procedures and results while pursuing explanatory coherence. This interplay is investigated in a laboratory learning environment, where students must coordinate procedural actions, interpretation of evidence, and explanation-building while carrying out experimental tasks. The study focuses on sustained *versus* disengaging sensemaking trajectories, understood here as the overall direction of students' sensemaking across the task rather than the success or failure of a single episode. This framing provides a basis for examining how knowledge gaps and epistemic emotions may be associated with whether students continue or withdraw from their efforts to make sense of the task.

The sensemaking process

Sensemaking has been recognized as a purposeful and motivated activity where learners actively engage with an examined phenomenon to develop a coherent explanation (Fitzgerald and Palincsar, 2019; Odden and Russ, 2019a). Sensemaking process has been conceptualized through several lenses that illuminate its different facets. As a cognitive process, it illustrates how learners build internal connections between prior knowledge and new scientific ideas (Odden and Russ, 2019a). As a discourse practice, it emphasizes the social and argumentative dialogue through which explanations are collaboratively constructed and critiqued (Ford, 2012; Odden and Russ, 2019a). And as an epistemological stance or ''frame,'' it represents a student's goal to genuinely ''figure something out'' rather than simply recall facts (Odden and Russ, 2018, 2019a). The focus on building explanatory coherence sets sensemaking apart from more general ''thinking'' or ''learning'' approaches and contrasts sharply with procedural approaches, such as ''answer-making'' (Chen *et al.*, 2013; Odden and Russ, 2019a; Hunter *et al.*, 2021).

Sensemaking is a dynamic process of building or revising an explanation to resolve a perceived gap or inconsistency in one's understanding (Odden and Russ, 2019a). The central goal is to ''figure something out'' by understanding the underlying mechanism of a phenomenon, moving beyond surface-level descriptions (Kapon, 2017; Odden and Russ, 2019a). This process is inherently dialogic, involving an iterative cycle of construction (proposing and connecting ideas) and critique (evaluating the coherence and plausibility of the emerging explanation) (Ford, 2012; Odden and Russ, 2019a). Critically, it involves drawing upon and attempting to reconcile a mix of everyday, intuitive knowledge and formal scientific knowledge to build a coherent explanation that resolves the recognized gap or inconsistency (Odden and Russ, 2019a).

To effectively support student sensemaking and design appropriate instruction, it is fruitful to view sensemaking as a process with distinct characteristics and a clear underlying trajectory. Conceptualizing sensemaking in this way facilitates the recognition, prediction, and exploration of the conditions, constraints, and factors that affect the process (Odden and Russ, 2018). Using the epistemic game framework as a theoretical lens, Odden and Russ (2018) modeled the sensemaking process as a distinct epistemic game that generally proceeds through four steps:

Step 0: assembling a knowledge framework. Before sensemaking can begin, students activate and connect relevant prior knowledge and experiences in an attempt to answer a question, explain a phenomenon, or make a prediction. This initial knowledge framework is dynamic and context-dependent, forming the cognitive foundation for the task at hand (Odden and Russ, 2018).

Step 1: noticing a gap or inconsistency. While using their assembled knowledge framework, students may fail to provide a coherent explanation or model, leading them to perceive a conflict, a missing connection, or an inconsistency in their understanding. This moment of noticing is the crucial entry condition that initiates the sensemaking game (Odden and Russ, 2018).

Step 2: generating an explanation. Once a gap is identified, students begin an iterative process of building and rebuilding an explanation to resolve it. This step is characterized by cycles of construction and critique, where students propose ideas, build analogies, coordinate multiple representations, and evaluate the coherence and plausibility of the emerging explanation (Ford, 2012; Odden and Russ, 2018, 2019b). Students attempt to construct a justified explanation by coordinating their claims with available data and articulating the reasoning that connects them (Osborne, 2014; Hunter *et al.*, 2021). Furthermore, this iterative process is often driven by the emergence of vexing questions. The act of repeatedly returning to these questions helps sustain the explanation-building through cycles of construction and critique (Odden and Russ, 2019b).

Step 3: resolution. The game can conclude successfully when students arrive at an explanation that, to their satisfaction, resolves the initial gap or inconsistency. The goal, or target epistemic form, is a coherent account, model, or explanation that resolves the perceived gap. However, the process can also end unsuccessfully if students are unable to develop a satisfactory resolution. This unsuccessful outcome is often accompanied by negative affective states, such as frustration or boredom, after repeated, failed attempts to resolve the inconsistency (Odden and Russ, 2018; Arguel *et al.*, 2019).

The catalyst for the entire sensemaking process is noticing a knowledge gap (Odden and Russ, 2019b; Chen, 2022). In the literature, these knowledge gaps have also been discussed as forms of scientific uncertainty and are often categorized as conceptual, procedural, and epistemic (Osborne, 2014; Chen, 2022, 2025; Ha *et al.*, 2024a; Chen *et al.*, 2025). Conceptual uncertainty refers to a struggle in using existing conceptions to explain a phenomenon, representing a gap in the ability to recognize, coordinate, and connect relevant conceptions (Chen, 2022; Chen *et al.*, 2025). Procedural uncertainty involves challenges in applying methods, experimental procedures, or algorithmic computations, reflecting a gap in knowing how to carry out scientific work (Osborne, 2014; Chen *et al.*, 2025). Finally, epistemic uncertainty encompasses uncertainty about

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the nature and justification of scientific knowledge itself, including how to formulate a question, interpret data, or construct a valid argument (Osborne, 2014; Chen, 2022; Chen *et al.*, 2025). A sensemaking process can involve any of these uncertainties, and progress toward explanatory resolution requires navigating all those that arise (Chen, 2022).

Cognitive load theory provides an additional perspective on why different types of knowledge gaps present varying levels of difficulty for learners. According to Sweller (1988, 2010), the cognitive complexity of a task depends on its element interactivity, which refers to the extent to which multiple elements must be processed simultaneously and in relation to one another. Tasks characterized by high element interactivity, such as those requiring conceptual integration or epistemic justification, place heavier demands on working memory. Procedural tasks, in general, tend to involve fewer interacting elements and can often be processed sequentially, thereby imposing a lower intrinsic cognitive load (Paas *et al.*, 2003; Ngu and Phan, 2016). However, procedural reasoning is not uniform in its cognitive demands. As noted by Stevenson (1994) and McCormick (1997), procedural activity can range from first-order procedures, which are automatic and algorithmic, to higher-order procedures that require strategic control and metacognitive regulation. Integrating cognitive-load theory with the epistemic game framework, therefore, provides a more nuanced explanation of how students navigate conceptual, procedural, and epistemic gaps during sensemaking.

Throughout the learning process, the emergence of uncertainty should not be viewed as a deficit to be avoided but as an opportunity to support student sensemaking. This uncertainty is the very engine that drives the development of coherence and, consequently, more integrated and meaningful learning (Odden and Russ, 2019b; Chen, 2022). These perceived gaps or inconsistencies often manifest as student-generated ''vexing questions,'' which are puzzling and affectively charged questions that students feel compelled to resolve. Such questions are instrumental in sustaining the sensemaking process, as they motivate students to persist, reshape their lines of inquiry, and critique existing explanations (Odden and Russ, 2019b). This creates a state of productive struggle, where students actively engage with uncertainty to construct a more robust and coherent understanding (Chen, 2022). This process of grappling with cognitive incongruity and the effort to resolve the vexation it causes is an inherently affective experience, involving a dynamic interplay of cognitive and emotional states.

Epistemic emotions

Emotions are complex sets of interrelated processes comprising affective, cognitive, physiological, motivational, and expressive components (Scherer and Moors, 2019). They are typically distinguished from moods and affect. Affect serves as an umbrella term encompassing emotions, moods, and related feelings. Moods, in contrast, are diffuse, global, low-intensity affective states of longer duration, but crucially, they lack a specific intentional object, which is the defining feature of emotions (Brun and Kuenzle, 2008). Two classical dimensions, namely valence (positive *vs.* negative) and activation (activating *vs.* deactivating), enable classification of emotions into four broad categories: positive activating (*e.g.*, curiosity, enjoyment), positive deactivating (*e.g.*, contentment), negative activating (*e.g.*, confusion, frustration, anxiety), and negative deactivating (*e.g.*, boredom) (Feldman Barrett and Russell, 1998; Pekrun, 2021).

Beyond valence and activation, emotions can also be differentiated by their object focus (Brun and Kuenzle, 2008). Pekrun's (2006) control-value theory (CVT) originally accounted for achievement emotions as arising from appraisals of control and value, distinguishing between activity-related and outcome-related emotions. The expanded CVT (Pekrun, 2021, 2024) broadened this framework to include four categories of emotions based on their object focus: achievement emotions (competent action), epistemic emotions (knowledge generation), social emotions (relating to others), and existential emotions (health and survival). Within this framework, epistemic emotions are defined by their object focus, as they pertain specifically to knowledge and the generation of knowledge itself, rather than to success or failure in task outcomes, which is the domain of achievement emotions (Brun and Kuenzle, 2008; Pekrun, 2021). In this study, eight epistemic emotions defined within Pekrun's (2021) expanded control-value theory – curiosity, surprise, confusion, anxiety, enjoyment, contentment, frustration, and boredom – were adopted as the analytic framework.

Epistemic emotions emerge from engaging with the cognitive qualities of tasks, particularly when learners encounter cognitive incongruity (Pekrun and Stephens, 2012). Such incongruity can evoke surprise and curiosity, trigger confusion when inconsistencies remain unresolved, or intensify into anxiety when contradictions threaten deeply held beliefs. It may culminate in enjoyment or contentment when understanding is achieved. Conversely, unresolved incongruity can lead to frustration or eventually boredom (D'Mello and Graesser, 2012; Pekrun, 2024).

Prior research shows that epistemic emotions can both support and hinder learning. Curiosity has been positively linked to learning and engagement (Bosch and D'Mello, 2017; Vogl *et al.*, 2019; Vogl *et al.*, 2020), whereas boredom and frustration are negatively associated with learning and frequently predict disengagement (Bosch and D'Mello, 2017). Confusion has a more complex role.

D'Mello and Graesser's (2012) model of cognitive disequilibrium provides a foundational framework for understanding the role of confusion in learning. It posits that confusion arises when learners encounter cognitive impasses, such as contradictory information or anomalous data, triggering a state of cognitive disequilibrium. The model, critically, differentiates between productive confusion, a transient state in which learners actively engage in effortful problem-solving to resolve impasses and restore equilibrium, and hopeless confusion, a persistent state characterized by frustration, boredom, disengagement, and, ultimately, a failure to learn.

Building on this distinction, Arguel *et al.* (2019) proposed a ''zone of optimal confusion,'' wherein moderate and resolvable

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levels of confusion act as an epistemic catalyst, motivating learners to invest greater cognitive effort, explore alternative solutions, and achieve deeper understanding. However, both models emphasize that when confusion exceeds this optimal threshold and persists or remains unresolved, it can overwhelm learners' cognitive resources, leading to frustration, boredom, disengagement, and diminished learning outcomes. Surprise also plays an ambiguous role, sometimes stimulating knowledge exploration (Vogl *et al.*, 2019; 2020) but at other times relating to less beneficial strategies (Bosch and D'Mello, 2017).

In science education, research on epistemic emotions is relatively recent but growing, with studies beginning to document how such emotions interact with instructional practices and learning outcomes (*e.g.*, Han and Gutierez, 2021; Vilhunen *et al.*, 2021, 2022; Han and Seok Oh, 2024; Agustian *et al.*, 2025; Stuppan *et al.*, 2025). For example, Vilhunen *et al.* (2022) found that curiosity and enjoyment correlated positively with performance, while frustration and boredom correlated negatively. Han and Seok Oh (2024) reported that in structured inquiry settings, curiosity and joy promoted persistence, while confusion and anxiety sometimes encouraged students to explore alternative approaches. Agustian *et al.* (2025) showed that laboratory work evokes a complex blend of curiosity, frustration, and joy, which are deeply intertwined with epistemic practices and the development of science identity. Taken together, these studies show that epistemic emotions are an integral component of science learning.

Rationale and research questions

Recent research in chemistry education illuminates key aspects of sensemaking in chemistry contexts. For example, Hunter *et al.* (2021) applied the sensemaking epistemic game framework to students' collaborative discussions in a gas laws activity. Through the claim–evidence–reasoning structure (McNeill *et al.*, 2006), Hunter *et al.* highlighted how student explanation can support and make sensemaking visible when students encounter new material. Extending this work to classroom interaction, Hamnell-Pamment (2024) examined teacher–student dialogue in a high school laboratory activity and highlighted the importance of teachers' discursive moves for maintaining a productive sensemaking process. This work draws attention to the social and emotional demands of sensemaking, particularly when teachers must reveal students' knowledge gaps without undermining their willingness to continue participating. In a different instructional context, Haraldsrud and Odden (2024) showed how computational simulations in physical chemistry can trigger and sustain sensemaking by generating discrepant feedback that challenges students' expectations and prompts iterative explanation and revision. Focusing on sensemaking through hybrid talk during practical work, Kolstø and Stadler (2025) analyzed upper-secondary students' dialogues in electrochemistry and showed how hybrid talk supported successful learning processes. Taken together, these studies provide important insights into how sensemaking may be supported through collaborative task contexts, classroom interaction, pedagogical tools, and practical work.

Despite these contributions, fewer studies have examined how sensemaking unfolds in undergraduate chemistry laboratory contexts as students engage with experimental procedures, evidence, and explanation-building. This gap is important because laboratories are central to undergraduate chemistry learning and provide opportunities to connect theoretical concepts and explanations with experimental practice and first-hand evidence (Hofstein *et al.*, 2001; Hofstein and Lunetta, 2004). Although recent work has highlighted epistemic and discursive challenges students encounter when explaining phenomena in laboratory settings (Pontigon and Talanquer, 2025), studies that examine cognitive and affective dimensions across contrasting sensemaking trajectories in undergraduate chemistry laboratory work remain limited.

This limitation is also theoretically significant; drawing on their sensemaking epistemic game framework, Odden and Russ (2018) identified several key research directions to clarify the sensemaking process, including the question: "for students who do not successfully complete the game, what factors lead them to end it prematurely?" (p. 14) Research has more often emphasized sustained sensemaking and explanatory progress than trajectories in which students disengage before reaching explanatory resolution (Ha *et al.*, 2024a, 2024b). Consequently, less attention has been paid to the processes associated with disengaging trajectories, including how different types of knowledge gaps and epistemic emotions may be related to whether sensemaking is sustained or begins to break down during laboratory work.

A related limitation is evident in research on epistemic emotions. To our knowledge, only one study has explicitly examined the relationship between epistemic emotions and sensemaking (Vilhunen *et al.*, 2023). In a three-cycle predict–observe–explain activity on the motion of a falling object, Vilhunen *et al.* (2023) identified distinct emotional trajectories, showing that upper-secondary students who generated relevant observations more often reported curiosity, surprise, and confusion, whereas those who struggled more often reported boredom. However, their analysis focused on a limited set of epistemic emotions and did not model sensemaking processes in depth or examine sustained *versus* disengaging sensemaking trajectories.

Building on this line of work, the present study examines the interplay of knowledge gaps and epistemic emotions in an undergraduate General Chemistry Laboratory course, with particular attention to sustained *versus* disengaging sensemaking trajectories. Within the broader research project, the present analysis is limited to focal cases from groups working without guidance during task engagement, in order to examine contrasting sensemaking trajectories as they unfolded through students' own efforts. The study aims to clarify how cognitive and affective processes are associated with different sensemaking trajectories during undergraduate chemistry laboratory work. In doing so, it contributes to sensemaking research in science education by extending trajectory-focused analysis to

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chemistry laboratory learning. It also offers practical relevance for chemistry instruction by showing how students' navigation of knowledge gaps and epistemic emotions differs across sustained and disengaging sensemaking trajectories.

Specifically, the study is guided by the following research questions:

(1) How do the types of knowledge gaps differ across sustained *versus* disengaging sensemaking trajectories in undergraduate chemistry students?

(2) How do patterns in undergraduate chemistry students' epistemic emotions differ across sustained *versus* disengaging sensemaking trajectories?

Methods

Research design

A holistic multiple-case study design was employed to investigate the phenomenon in depth. A case study explores a setting, individual, event, or process in detail within a bounded system (Yin, 2018). According to Merriam (2009), ''for it to be a case study, one particular program or one particular classroom of learners (a bounded system) or one particular older learner selected based on typicality, uniqueness, success, and so forth would be the unit of analysis'' (p. 41). Accordingly, the present study adopts a case study design, as it aims to investigate in depth the sensemaking processes of undergraduate chemistry students, as well as the epistemic emotions that arise during these processes, within a specific bounded context of the General Chemistry Laboratory course, using multiple data collection tools such as video and audio recordings, the activity sheet, and emotion diaries. In this study, sensemaking episodes that emerged within this bounded context served as the primary analytic units. These episodes were examined comparatively in order to characterize the broader task-level trajectories of the two focal cases, namely sustained and disengaging sensemaking trajectories. Knowledge gaps and epistemic emotions were analyzed as analytical dimensions that illuminated how these trajectories unfolded as students made sense of chemistry in the laboratory.

Broader project context

The data for this study were derived from a larger research project on student sensemaking conducted at a public university in Türkiye. The project was conducted with first-year undergraduate students enrolled in a chemistry education program. A total of 18 students (14 females and four males) were included in the project. Criterion sampling was used, with enrollment in the General Chemistry Laboratory II course during the spring semester of the 2024–2025 academic year serving as the inclusion criterion (Patton, 2014). All enrolled students met the criterion; therefore, the full cohort of 18 students was included. The General Chemistry Laboratory II course was selected because it provides an appropriate context for examining students' sensemaking processes related to chemistry concepts. All participants had completed the General Chemistry Laboratory I course during the fall semester of the same academic year. Whereas the first course emphasized laboratory safety and the use of chemicals and materials and was conducted primarily in a traditional, procedure-oriented format, the second focused more exclusively on experimental practices. At the time of the project, participants were also concurrently enrolled in the theoretical General Chemistry II course, and the laboratory experiments were conducted after the corresponding topics had been covered in that course. Ethical approval was obtained from the university's review board, and all participants provided informed consent.

Prior to research data collection, participants received instruction on the nature and categories of epistemic emotions to support consistent use of the emotion diary during laboratory work. Throughout the 15 week semester, students attended weekly two-hour laboratory sessions and conducted experiments in five heterogeneous groups, each consisting of three or four students. Students were assigned to groups structured to ensure within-group heterogeneity based on their GPAs, and they agreed to work within these assigned groups throughout the semester.

Within the broader project, six chemical thinking-based, inquiry-based laboratory activities were implemented in General Chemistry Laboratory II under varying small-group guidance conditions. During all experiments, the course instructor, who was also one of the researchers, was present. Because the data were collected as part of a course, supporting students' attainment of the intended learning objectives was essential. The instructor therefore provided conceptual explanations at the end of the activity to offer pedagogical closure and to support students in developing a coherent understanding of the key chemistry ideas involved in the laboratory activity, only after data collection for the activity had been completed so that it would not influence the data collection process. Further details of the broader project structure, including the preparation for epistemic emotion reporting and the instructional organization of the laboratory activities, are provided in the supplementary information (SI).

Participants and research setting of the current study

Because the aim of the current study was to examine how students' sensemaking trajectories unfolded without ongoing small-group guidance during task work, the sample was drawn exclusively from groups that worked without small-group guidance. Across the broader project, which included six chemical thinking activities, data from two groups working without small-group guidance were available for each activity, resulting in 12 group cases in total. Among these cases, the Boyle's law activity was the only context in which two groups working without small-group guidance exhibited contrasting trajectories (sustained *versus* disengaging sensemaking trajectories), thereby allowing a comparable within-activity contrast.

In this study, sustained *versus* disengaging sensemaking trajectories refer to the task-level pattern of students' sensemaking across the activity. This framing was adopted to capture whether students continued working toward explanatory

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coherence or gradually withdrew from task-related sensemaking efforts, rather than to classify a single episode as successful or unsuccessful. A group could therefore exhibit locally successful sensemaking episodes at particular moments while still following an overall disengaging trajectory across the task.

The participants of the current study were selected using outlier sampling (also referred to as extreme or deviant case sampling), a purposive sampling strategy that focuses on information-rich cases that are unusual or distinctive, such as unusually sustained or disengaging patterns of sensemaking (Patton, 2014), in order to examine contrasting sensemaking trajectories.

The focal cases consisted of two groups that worked without small-group guidance: Group 1, which exhibited a sustained sensemaking trajectory, included one female and two male students; and Group 2, which exhibited a disengaging sensemaking trajectory, included three female and one male student. In total, the current study was based on data from seven participants. The participants in Groups 1 and 2 had mean ages of 19 and 21 years, and the GPAs of 2.14 and 1.92 out of 4.00, respectively.

For groups working without small-group guidance, the instructor intervened only when necessary to maintain the continuity of the activity and address safety concerns, while avoiding any influence on the substance of students' group discussions. Moreover, the instructor reviewed the procedures designed by these groups for potential safety concerns and approved only those deemed safe to conduct. Thus, in the present study, working without small-group guidance did not mean the absence of instructor oversight; rather, it meant the absence of ongoing guidance directed at the substance of students' sensemaking during task engagement.

Data collection tools

Data for this study were collected through audio and video recordings of group work, the completed Boyle's law experiment activity sheets, and individual student emotion diaries.

The Boyle's law activity sheet. A chemical thinking-based activity on Boyle's law was developed by the research team in accordance with the framework proposed by Talanquer and Pollard (2010) and related work on chemical thinking (Sevian and Talanquer, 2014; Talanquer, 2018) (see SI). The activity was designed to provide opportunities for multiple sensemaking episodes. In the activity sheet, students were first presented with a real-life scenario explaining how natural gas technicians detect gas leaks using a water-filled U-tube manometer, thereby situating the task in an authentic context. Following this introduction, the main task was outlined. Students were asked to design and then conduct an experiment to investigate the pressure–volume relationship for a fixed amount of air using a U-tube manometer, water, and a syringe, and to produce a graphical representation of the data they collected. The activity sheet also included a concise reminder of Boyle's law to support students' engagement with the task. In addition, it contained structured stages that students were required to complete, covering designing the experiment, conducting the experiment and collecting data, results of the experiment, and the interpretation of the results.

The epistemic emotion diary. The epistemic emotion diary, developed by the research team based on Pekrun's (2021) framework, prompted students to report the epistemic emotions they experienced and their perceived causes across five task stages: encountering the task, designing the experiment, conducting the experiment and collecting data, results of the experiment, and the interpretation of the results (see SI). When the epistemic emotion diaries were collected, any ambiguous entries were clarified through follow-up questions, and students were asked to provide more detailed explanations where necessary. To gain a deeper understanding of the epistemic emotions reported, students were also asked to indicate the specific reason or situation that elicited each emotion. The epistemic emotion diaries were collected at the end of the experiment to avoid interrupting students' engagement during laboratory work.

As described earlier, students received prior instruction on epistemic emotions before research data collection began. The purpose of this instruction was to clarify the epistemic emotion categories and to support consistent use of the emotion diary during subsequent hands-on laboratory work. In addition, because the Boyle's law activity was the third laboratory activity from which data were collected in the broader project (see SI), students had already completed the emotion diary twice prior to this activity, which helped familiarize them with the reporting procedure.

Data analysis

After transcribing all audio and video recordings, the whole dataset was analyzed using thematic analysis following Braun and Clarke's (2006) six-phase approach. All transcripts were coded and managed in MAXQDA Pro Analytics 2024. Participants' sensemaking was examined through the four-stage epistemic game framework proposed by Odden and Russ (2018). Step 0 captured instances where participants activated prior knowledge or everyday experiences, and was used as the common starting point for all identified sensemaking episodes. Step 1 marked the emergence of a conceptual, procedural, or epistemic knowledge gap. Step 2 involved constructing explanations in response to the gap, indicated by a ''vexing question,'' and was characterized by efforts to build robust explanations. As part of Step 2, claim-evidence-reasoning (CER) chains were analyzed as an indicator of the quality of explanations. Because such explanations were constructed only in successful sensemaking episodes, CER coding was conducted exclusively for this subset of the data, derived by the coders through inferences from the often fragmented dialogues. Step 3 reflected the group's arrival at a shared, coherent explanation, although the consensus reached did not necessarily have to be scientifically accurate. At the episode level, episodes completing Steps 0–3 were coded as ''Successful Sensemaking'', while those with an ineffective Step 2 and lacking a Step 3 were coded as ''Unsuccessful Sensemaking'' (T.O.B., Odden, & A. Haraldsrud, personal communication,

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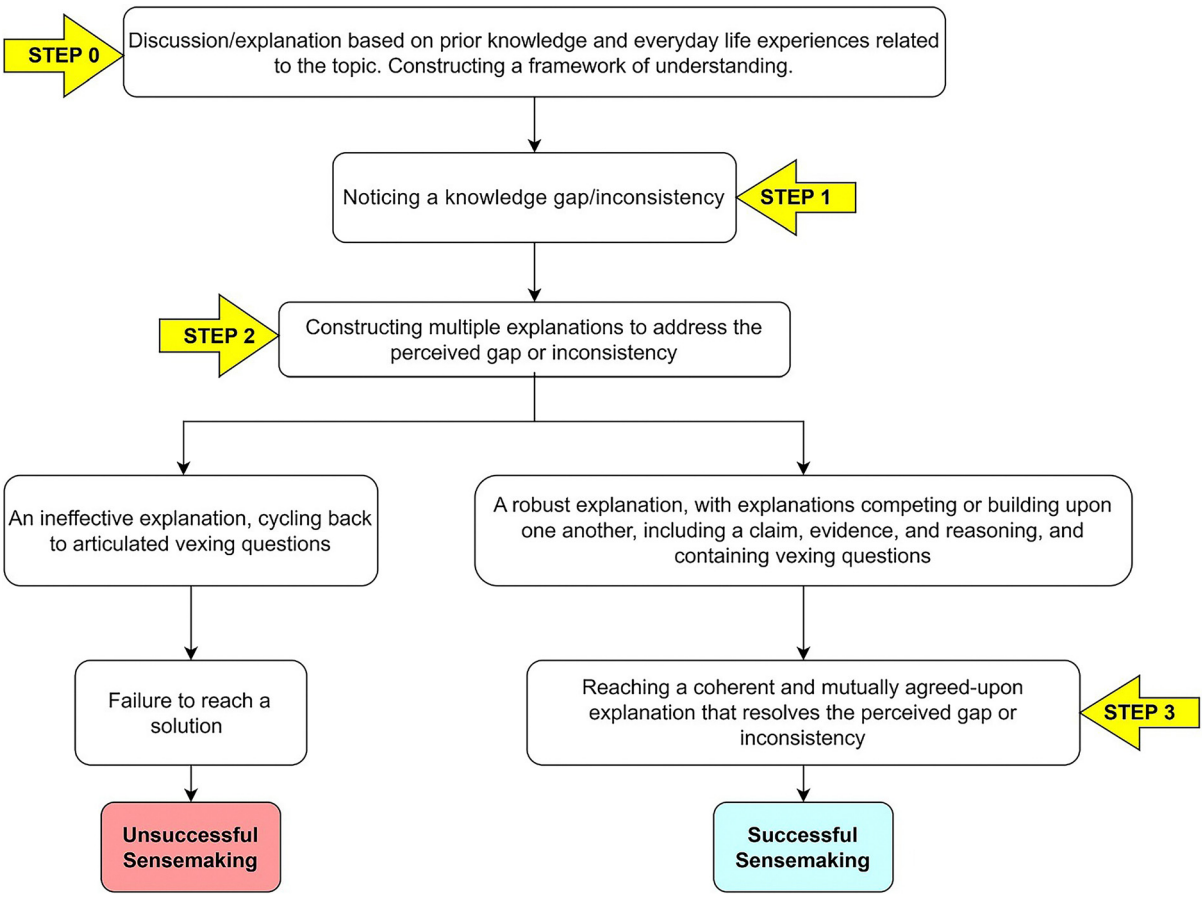


Fig. 1 The complete coding scheme (Odden and Russ, 2018; T.O.B., Odden & A. Haraldsrud, personal communication, June 4, 2025).

June 4, 2025). These episode-level codes were used to characterize the broader sustained and disengaging sensemaking trajectories examined across the task. The complete coding scheme is provided in Fig. 1, and the accompanying codebook is provided in SI.

In Step 1, knowledge gaps were classified as conceptual, procedural, or epistemic (Osborne, 2014; Chen, 2022, 2025; Ha *et al.*, 2024a; Chen *et al.*, 2025). Conceptual gaps refer to difficulties in explaining phenomena due to incomplete, conflicting, or insufficient conceptual understanding. Procedural gaps encompass students' difficulties understanding and applying scientific methods, problem-solving processes, or experimental procedures. Epistemic gaps involve uncertainty about the nature and justification of scientific knowledge.

Participants' epistemic emotions were analyzed descriptively using Pekrun's (2021) framework, classifying them by valence and activation level. Epistemic emotions were categorized as positive or negative according to their valence, and as activating or deactivating depending on their level of behavioral arousal (Pekrun *et al.*, 2017). A detailed coding framework is provided in Table 1.

Trustworthiness of the study

To ensure the trustworthiness of the study, several strategies were employed in line with Lincoln and Guba's (1985) framework. Credibility was strengthened in multiple ways. Prolonged engagement was achieved by conducting the study in the General Chemistry Laboratory II course while also working with the same students during the previous semester in the

Table 1 Epistemic emotions coding framework

Dimension	Category	Definition	Epistemic emotions
Valence	Positive	Experienced pleasant emotions	Curiosity, enjoyment, surprise, contentment
	Negative	Experienced unpleasant emotions	Confusion, frustration, anxiety, boredom
Activation	Activating	The emotion experienced drives the person to perform	Curiosity, surprise, enjoyment, confusion, anxiety, frustration
	Deactivating	The emotion experienced drives the person not to perform	Contentment, boredom

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General Chemistry Laboratory I course. This provided continuous exposure to the research environment, familiarized students with video recordings, and allowed for pilot implementations, thereby fostering trust and comfort. Member checking was implemented through the epistemic emotion diaries, in which students reported their emotions and underlying causes and were later asked to confirm these reflections. Expert review was sought to refine the coding framework for sensemaking episodes. Triangulation was achieved by drawing on multiple data sources, including audio and video recordings of group work, completed Boyle's law activity sheets, and individual student emotion diaries. Dependability was supported by a multi-stage coding process. Nine members of the research team first engaged in a joint calibration session to establish a shared understanding of the coding scheme and refine the codebook. Subsequently, two researchers independently examined the transcripts to identify potential sensemaking episodes. Intercoder reliability (IRR) was assessed at the segment level using percent agreement. Discrepancies were resolved through discussion and consensus, resulting in a finalized set of episodes. Although the comparative framing of this paper focuses on sustained and disengaging trajectories at the task level, coding reliability was established at the segment level for multiple analytic steps, including sensemaking episode identification and knowledge gap coding, both of which provided the analytic basis for characterizing those broader trajectories. Accordingly, the IRR results for sensemaking episode identification are reported only for the two focal groups, which exhibited contrasting task-level sensemaking trajectories (Group 1, sustained; Group 2, disengaging) (percent agreement = 88%). This value falls within the commonly accepted range for qualitative coding (Miles and Huberman, 1994). Once episodes were finalized, their constituent steps (Steps 0–3) were coded collaboratively through consensus. Step-level coding was treated as part of the episode structure and therefore not subjected to separate IRR analyses. In addition, the portions of each episode corresponding to Step 1 (identifying a gap or inconsistency) were independently coded by two researchers to determine the type of knowledge gap involved (procedural, conceptual, or epistemic). The IRR for knowledge gap coding was assessed using percent agreement (78%), which likewise falls within the acceptable range for qualitative coding. Any discrepancies were resolved through discussion and negotiated consensus. Finally, CER chains, which often spanned fragmented contributions across multiple speakers, were reconstructed holistically by the researchers and coded through consensus, with reliability ensured through negotiated agreement rather than statistical IRR. Transferability was facilitated by providing thick descriptions of the research context, participant groups, and representative sensemaking episodes, enabling readers to judge the applicability of the findings to other contexts. Confirmability was ensured by maintaining an audit trail of coding files, consensus versions, and analytic memos, as well as through peer debriefing sessions within the research team, which minimized bias and grounded interpretations in the data.

Results

The results are organized under two main sections corresponding to the research questions. The first section examines the types of knowledge gaps that emerged across the sustained and disengaging sensemaking trajectories represented by the two focal groups (RQ1). The second section explores how students' epistemic emotions varied across these contrasting sensemaking trajectories (RQ2).

RQ1. How do the types of knowledge gaps differ across sustained *versus* disengaging sensemaking trajectories in undergraduate chemistry students?

Tables 2 and 3 present the knowledge gaps identified in both groups during their sensemaking processes, the types of these gaps, and the explanations constructed by the students in an attempt to resolve them. These gaps were repeatedly articulated by students through vexing questions during Step 2 of the sensemaking process. The explanations through which each group reached consensus were subsequently analyzed using the CER framework to evaluate their quality. Taken together, these episode-level analyses provide the basis for understanding how the two groups followed sustained and disengaging sensemaking trajectories across the task.

As shown in Table 2, Group 1 encountered five procedural gaps during the activity. These were all resolved by the group based on CER-based explanations. This pattern suggests that Group 1 was able to work through the procedural demands of the task while maintaining explanation-building efforts, which was consistent with its sustained sensemaking trajectory.

Table 3, presenting Group 2's sensemaking processes, shows that the group encountered five knowledge gaps in total, comprising three conceptual, one procedural, and one epistemic gap. Although Group 2 successfully resolved the procedural gap, they were unable to construct CER-based explanations for the conceptual and epistemic gaps that remained unresolved. This pattern indicates that the unresolved conceptual and epistemic gaps co-occurred with the group's inability to sustain explanation building toward a shared resolution.

Table 4 comparatively summarizes this contrast by presenting the knowledge gaps experienced by Groups 1 and 2, their types, and the episode-level sensemaking outcomes associated with these gaps. Group 1 resolved all five procedural knowledge gaps it encountered, and the episodes associated with these gaps resulted in successful sensemaking. This overall pattern was consistent with a sustained sensemaking trajectory. By contrast, Group 2 resolved only the procedural gap, yielding a single successful sensemaking episode. Its conceptual and epistemic gaps, however, remained unresolved and were associated with unsuccessful sensemaking episodes. Taken together, the pattern across these episodes contributed to an overall disengaging sensemaking trajectory, with the group ultimately withdrawing from the activity before reaching a coherent explanation.

The following excerpts illustrate successful and unsuccessful sensemaking episodes, together with the knowledge gaps

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Table 2 Knowledge gaps identified in Group 1 and the explanations constructed to resolve them

Knowledge gap	Type of knowledge gap	Explanation
How to measure pressure and volume using a manometer	Procedural	Claim: pressure is measured by injecting air with a syringe; the volume can then be calculated from the equation $P = F/A = m{\cdot}g/A = V{\cdot}\rho{\cdot}g/A$ Evidence: the instructor's explanation about how to use the syringe and the formulas related to pressure provided in the activity sheet Reasoning: when air is injected with the syringe, the difference in the water levels in the manometer gives the value of P_h; once P_h is found, the volume (V) can be calculated using the equation $P = V{\cdot}\rho{\cdot}g/A$
Where to use the vapor pressure of water	Procedural	Claim: to determine the gas pressure (P_{gas}), the vapor pressure of water is subtracted after obtaining the total pressure Evidence: the vapor pressure value of water at the temperature specified in the activity sheet, and the fact that the gas whose pressure and volume are measured is located in the closed arm of the apparatus (manometer) Reasoning: the water vapor accumulated above the liquid inside the manometer exerts pressure; the vapor pressure of water is therefore taken into account when calculating the pressure of the gas (P_{gas}) collected in the closed arm of the manometer
Whether the syringe plunger should be pushed or pulled to obtain the volume data	Procedural	Claim: during the experiment, the syringe plunger is pushed Evidence: the water level in the open arm rises when the syringe plunger is pushed and falls when it is pulled Reasoning: since the water level in the open arm of the manometer is higher, as indicated in the activity sheet, the plunger should be pushed
How to determine the gas volume using the manometer apparatus	Procedural	Claim: the volume of the gas in the syringe is taken as V_{gas} Evidence: the volume measurements in the syringe and the difference in water levels between the arms of the manometer Reasoning: according to Boyle's law, pressure (P) and volume (V) are inversely proportional; as the syringe plunger is pushed and the gas volume decreases, the pressure measured by the manometer increases
How to use the units when calculating $P_{gas} = P_h + P_{atm}$	Procedural	Claim: all units are converted to mmHg to calculate P_{gas} Evidence: the atmospheric pressure given in the activity sheet is in mmHg (P_{atm} = 760 mmHg), and the unit conversion formula related to the hydrostatic pressure of water [P (mmHg) = h_{water} (mm) × 1.00/13.6] Reasoning: all units must be the same in addition operations. Since the atmospheric pressure is given in mmHg, P_h is also calculated in mmHg when determining P_{gas}

Table 3 Knowledge gaps identified in Group 2 and students' attempts to resolve them

Knowledge Gap	Type of Knowledge Gap	Explanation
What is measured with the syringe connected to the manometer and the water levels in the manometer arms (P or V)	Conceptual	No CER-based explanation: students had difficulty establishing the conceptual relationship among the compressibility of gases, the constant number of moles, the inverse proportionality of P–V, and its representational measurement
What is added or removed with the syringe (air, pressure, *etc.*)	Conceptual	No CER-based explanation: students were unable to conceptually distinguish whether syringe movement changed the amount of gas, the pressure, or the volume. The difficulty lay not in carrying out the procedure, but in understanding what the syringe movement represented in relation to the gas in the closed system and why the number of moles remained constant
The fact that the difference between the liquid levels in the manometer remains unchanged whether the syringe plunger is pushed or pulled by the same amount	Conceptual	No CER-based explanation: students were unable to conceptually explain why equal amounts of pushing and pulling produced the same level difference in the manometer and how this related to the P–V relationship
Whether the syringe plunger should be pushed or pulled to obtain the volume data	Procedural	Claim: during the experiment, the syringe plunger is pulled Evidence: when the syringe plunger is pushed or pulled by the same amount, the difference between the liquid levels in the manometer does not change Reasoning: since pushing or pulling the syringe plunger has the same effect, the easier action-pulling-should be performed.
The inconsistency of the experimental data with Boyle's law	Epistemic	No CER-based explanation: students were unable to develop a reasoned explanation based on measurement error, experimental method, or theoretical considerations to account for the mismatch between their experimental data and the inverse proportionality predicted by Boyle's law

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Table 4 Types of knowledge gaps and sensemaking outcomes for Groups 1 and 2

Type of knowledge gap	Group 1		Group 2	
	N	Outcome	*N*	Outcome
Procedural	5	S-SM	1	S-SM
Conceptual	—	—	3	U-SM
Epistemic	—	—	1	U-SM

Note: S-SM = successful sensemaking episode; U-SM = unsuccessful sensemaking episode. These refer to episode-level outcomes.

that triggered them, within the sustained and disengaging trajectories observed in Groups 1 and 2. Instruction and discussions were conducted in Turkish. Audio recordings were transcribed in Turkish and translated into English for reporting purposes by the research team. The groups initiated their sensemaking processes by reading the task in the activity sheet and engaging in discussions that drew on their prior knowledge and everyday life experiences related to the task. This stage, coded as Step 0 and serving as the knowledge framework for all sensemaking processes, represented a common starting point within each group's sensemaking trajectory. Therefore, the tables that present the sensemaking episodes (Fig. 2–4) begin with Step 1.

Example of a successful sensemaking episode involving a procedural gap within Group 1's sustained trajectory. An example of a successful sensemaking episode from Group 1 is presented in Fig. 2. The excerpt revolves around the vexing question, "Vapor pressure data were given. Where will we use it?" (Line 1). This gap was coded as procedural because the group's discussion focused on how to incorporate vapor pressure into their calculations and whether it should be applied to the open or closed end of the manometer. This episode illustrates how, within Group 1's sustained sensemaking trajectory, an initial state of confusion was transformed into a coherent explanation. During Step 2, Group 1 decided to subtract the vapor pressure of water (Line 27), provided in the activity sheet, from the measured pressure to determine the pressure of the gas (air) in the closed system (Lines 10-15). As justification, they stated that the water vapor accumulated above the water inside the manometer exerted pressure and that the vapor pressure of water should be considered in calculating the pressure of the gas (P_{gas}) collected in the closed end of the manometer (Lines 23, 30, and 36).

Examples of unsuccessful sensemaking episodes involving conceptual and epistemic gaps within Group 2's disengaging trajectory. Group 2 encountered both conceptual and epistemic gaps, which remained unresolved during the activity. These unresolved gaps contributed to the group's inability to complete the task and were associated with its overall disengaging sensemaking trajectory. The episode presented in Fig. 3 centers on a conceptual gap related to gas behavior. The question, "[When we push the syringe] are we adding something, then?" (Line 1), triggered this conceptual gap. In fact, the experimental setup functioned as a closed system in which no gas was added or removed; the movement of the plunger altered only the

..STEP 1	1	S1: *Vapor pressure data was given. Where will we use it?*
	2	S2: There is water inside [the manometer].
	3	S1: That's why they gave the vapor pressure.
	4	S2: That's the pressure—because of the water inside.
	5	S1: *But I mean, in which equation will we use the vapor pressure?*
	6	S2: It says ρ [density] water, look. It says h water.
	7	S1: h water, ρ water.
	8	S2: Then we won't be using it.
	9	S1: *But what should we do?*
	10	S2: We can use the equation above [hwater . ρwater . g = hHg . ρHg . g]
	11	S1: They wouldn't have given it for nothing.
	12	S3: Wait a second, what does it say there?
	13	S1: Here?
	14	S3: Yeah.
	15	S1: It says to collect and record the data here. It also says to take the vapor pressure of water as 23.8 mmHg at 1 atm air pressure and 25°C.
	16	S3: Okay, like this.
	17	S1: We'll write it here. It says P mmHg, right? ρwater, that's correct.
	18	S1: We'll write it here, I think.
	19	S3: No, we will write what we found here. No, it says here that it should be calculated in mmHg — I mean, in millimeters of mercury. For example, let's say your pressure...
	20	S1: Ah, okay okay. They've given the density of water here. Okay, I got it.
..STEP 2	21	S3: That's after you find this pressure.
	22	S1: That's already easy.
	23	S3: I think the pressure is like this. Remember the mole fraction thing and so on. They've given us the vapor pressure of water, right? When gases are collected over water, we use the vapor pressure of water, do you remember?
	24	S1: Yes.
	25	S3: Okay, so what unit did they give us?
	26	S1: They gave it in millimeters of mercury. Okay
	27	S3: Then, after finding the pressure inside in millimeters of mercury, we have to subtract the vapor pressure of water from it. I think so.
	28	S1: Oh, you mean because there's water inside, the air will push it, like when a gas is collected over water.
	29	S3: Wait a second, I didn't understand that.
	30	*S1: Should you consider the vapor pressure of water in an open system or a closed system? I think you consider it in a closed system, but not an open one.*
	31	S3: Ok. Don't we have to subtract the vapor pressure at the end anyway?
	32	S2: Isn't it already given as 23.8?
	33	S3: Ok, aren't we going to subtract that at the end anyway? Open or closed... I don't get where you would apply it in an open system.
	34	S1: . I'm not going to apply it in the open one now.
	35	S3: I didn't understand which part is the open system.
	36	S1: No, when I say open system, I mean this part is actually closed after all.
	37	S3: Ok. What do you think about this?
..STEP 3	38	S1: Actually, it makes sense.
	39	S3: So you're okay with this? [To S2, S2 nods in agreement.]

Note. Square brackets indicate author clarifications. "S" stands for "Student". The italic font stands for the vexing question.

Fig. 2 Example of a successful sensemaking episode resolving a procedural gap in Group 1.

volume of the gas. The students' subsequent discussion suggested difficulty in understanding gas behavior, the mole concept, and the pressure–volume relationship, pointing to challenges in applying underlying scientific principles rather than in carrying out a procedure. The students were unable to reconcile their ideas about whether pushing the syringe added or removed gas and how pressure and moles were affected, leading to a cycle of recurring vexing questions without resolution (Lines 5, 10, 18, and 19). Because the conceptual gap remained unresolved, the group could not progress to Step 3, and the episode therefore resulted in unsuccessful sensemaking.

When Group 2 recognized that their experimental data did not align with Boyle's law, they encountered an epistemic gap because they were uncertain how to interpret this discrepancy. The inconsistency between the observed pressure-volume changes and the relationship predicted by Boyle's law raised doubts about the accuracy of their measurements as well as

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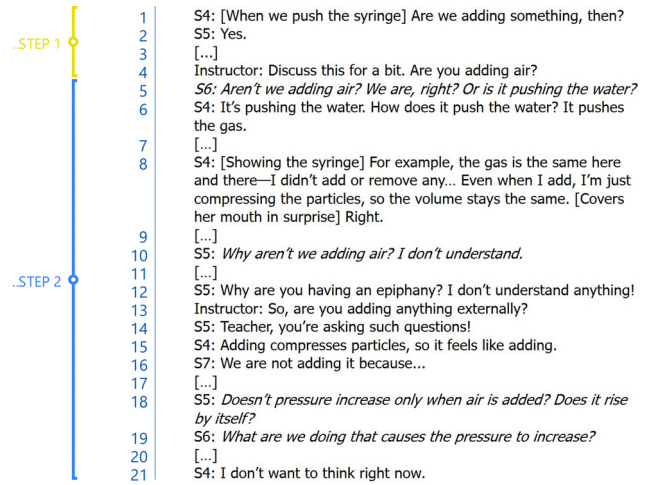


Fig. 3 Example of an unsuccessful sensemaking episode involving a conceptual gap in Group 2.

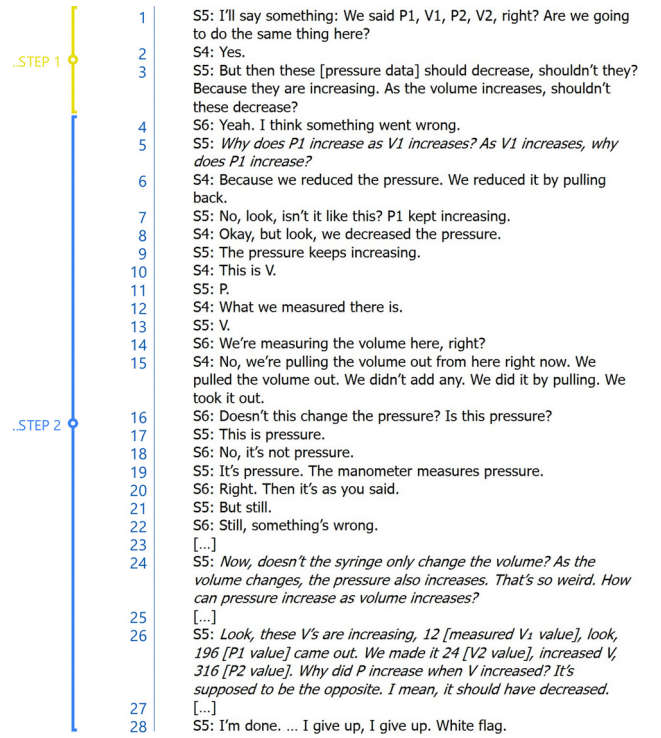


Fig. 4 Example of an unsuccessful sensemaking episode involving an epistemic gap in Group 2.

about how scientific knowledge should be used to make sense of unexpected results. The question in Fig. 4, "But then these [pressure data] should decrease, shouldn't they? Because they are increasing. As the volume increases, shouldn't these decrease?" (Line 3), triggered this gap. The students posed a series of questions to make sense of the observed pressure–volume relationship but failed to reach a common conclusion. Repeated vexing questions such as "Why does P1 increase as V1 increases? As V1 increases, why does P1 increase?" (Line 5) and "Doesn't the syringe only change the volume? As the volume changes, the pressure also increases. That's so weird. How can pressure increase as volume increases?" (Line 24) indicated that the group was unable to reconcile the relationship predicted by Boyle's law with their experimental findings. Discussions about how the pressure and volume variables were measured, how they influenced one another, and why the data failed to exhibit the expected inverse relationship remained unresolved. As these issues persisted, the group's sensemaking efforts gradually gave way to hopeless confusion. Consequently, they were unable to construct a coherent explanation and ultimately terminated the discussion. Because this epistemic gap remained unresolved, the group could not progress to Step 3 of the sensemaking process, and the episode therefore resulted in unsuccessful sensemaking. More broadly, this unresolved gap was closely associated with Group 2's inability to complete the task and with its overall disengaging trajectory.

RQ2. How do patterns in undergraduate chemistry students' epistemic emotions differ across sustained *versus* disengaging sensemaking trajectories?

In this section, we present the epistemic emotions reported by the two groups across different stages of the activity, highlighting how their emotional trajectories diverged across the sustained and disengaging sensemaking trajectories observed in the study. Table 5 summarizes the emotions reported across the five stages of the task, organized according to Pekrun's (2021) taxonomy of epistemic emotions. Group 1, which exhibited a sustained sensemaking trajectory and completed the activity, largely maintained positive emotions throughout the task. In contrast, Group 2, which exhibited a disengaging sensemaking trajectory and withdrew before completing the activity, exhibited a marked shift toward negative emotions.

During the activity, both groups initially reported positive activating epistemic emotions, such as curiosity and surprise, when encountering the task. Quantitatively, almost all emotions at this stage were positive activating (six out of seven reported emotions). However, from the designing the experiment stage onwards, the groups' emotional trajectories diverged. Although both groups experienced confusion at this stage, the emotional context differed. For Group 1, confusion co-occurred with positive activating emotions, suggesting engagement and intellectual stimulation. Across the following three stages, eight of the 11 reported emotions were positive (*e.g.*, curiosity, enjoyment, contentment), while only a few were negative (*e.g.*, confusion). Enjoyment and contentment became particularly salient during the results and interpretation stages, which was consistent with Group 1's sustained sensemaking trajectory. By contrast, Group 2 experienced confusion in conjunction with negative emotions such as anxiety and boredom in the designing the experiment stage. Among the ten emotions reported during the latter three stages, nine were negative (*e.g.*, anxiety, confusion, boredom, frustration), and five of these negative emotions were deactivating. The negative deactivating emotion, boredom, was reported five times. In the final stage of

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Table 5 Epistemic emotions reported across the stages of the activity (N = 7)

	Group 1 (n = 3)				Group 2 (n = 4)			
	Positive emotions		Negative emotions		Positive emotions		Negative emotions	
Stages of the activity	Act.	Dea.	Act.	Dea.	Act.	Dea.	Act.	Dea.
Encountering the task	ENJ$\surd$ CUR$\surd$ SUR$\surd$	—	—	—	CUR $\surd\surd\surd$	—	CON$\surd$	—
Designing the experiment	SUR$\surd$ CUR$\surd\surd$	—	CON$\surd$	—	—	—	CON $\surd\surd\surd$ ANX$\surd\surd$	BOR$\surd$
Conducting the experiment and collecting data	ENJ$\surd$ CUR$\surd$	—	ANX$\surd$	BOR$\surd$	SUR$\surd$	—	CON$\surd\surd$	BOR$\surd$
Results of the experiment	ENJ$\surd\surd$	CNT$\surd\surd$	—	—	—	—	CON$\surd$	BOR$\surd\surd$
Interpretation of the results	ENJ$\surd\surd$	—	—	BOR$\surd$	—	—	FRU$\surd$	BOR$\surd\surd$

Note: Act. = activating, Dea. = deactivating, ENJ = enjoyment, CUR = curiosity, SUR = surprise, CNT = contentment, CON = confusion, ANX = anxiety, BOR = boredom, FRU = frustration, $\surd$ indicates the number of times an emotion was reported, and "—" indicates that no emotion was reported in that category.

the activity, boredom and frustration prevailed, which was consistent with Group 2's disengaging sensemaking trajectory.

While Table 5 provides detailed frequencies of reported emotions across stages, Fig. 5 and 6 offer complementary visualizations that highlight broader patterns and contrasts between the groups' emotional trajectories. The radar chart in Fig. 5 illustrates the overall trajectories of the two groups' epistemic emotions, based on the percentage distribution of reported emotions across four intersecting categories: positive, negative, activating, and deactivating. Because each emotion was coded along both valence (positive–negative) and activation (activating-deactivating) dimensions, the total number of coded instances per group (n = 18 for Group 1; n = 20 for Group 2) reflects overlapping classifications rather than discrete emotion events. Percentages were calculated relative to the total number of coded instances for each group, allowing for a normalized comparison. While Group 1's trajectory was dominated by positive activating emotions, Group 2's trajectory was shaped primarily by negative activating ones. The contrasting shapes of the two radar plots thus visually emphasize the divergent emotional patterns associated with the sustained and disengaging sensemaking trajectories observed in the two groups.

Fig. 6 presents the groups' epistemic emotion trajectories across the stages of the activity, based on normalized valence and activation indices. Group 1 exhibited consistently more positive emotional trajectories, with peaks at the beginning of the activity and during the results stage, whereas Group 2 displayed predominantly negative emotional trajectories, particularly from the experimental design stage onwards. With respect to activation, both groups' emotions remained predominantly activating overall, although Group 2 showed a slight shift toward the end of the activity.

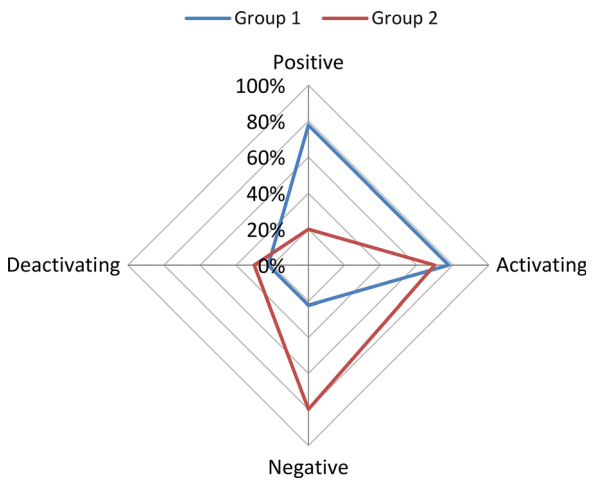


Fig. 5 Groups' epistemic emotion tendencies.

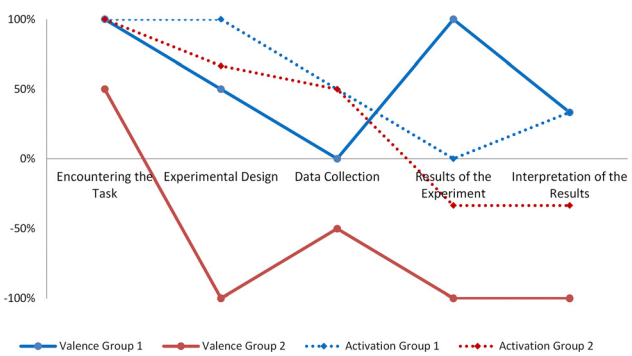


Fig. 6 Relative trajectories of epistemic emotions across the activity stages for Groups 1 and 2, based on normalized indices of emotional valence and activation. Valence was calculated as (Positive − Negative)/(Positive + Negative), and activation was calculated as (Activating − Deactivating)/(Activating + Deactivating). The resulting values were converted into percentages to allow proportional comparison across groups. For both indices, positive values indicate a predominance of positive or activating emotions, whereas negative values indicate a predominance of negative or deactivating emotions.

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Discussion

The findings highlighted that, during Boyle's law activity, the types of knowledge gaps students experienced, along with their epistemic emotions, were associated with variations in their sensemaking trajectories. In the present study, by examining students' sensemaking processes within the context of chemistry laboratory activities, procedural knowledge gaps also emerged as an additional category, as in Chen *et al.*'s (2025) study, illuminating how students make sense of chemical phenomena and extending existing frameworks that primarily focus on conceptual and epistemic gaps (Ha *et al.*, 2024a, 2024b ; Chen, 2025). Group 1 encountered procedural knowledge gaps and resolved all of them, a pattern that was consistent with its sustained sensemaking trajectory. In contrast, Group 2 resolved only one procedural gap, whereas its conceptual and epistemic gaps remained unresolved. This pattern was closely associated with the group's disengaging trajectory and its eventual withdrawal from the task before reaching explanatory coherence.

Although the resolution of procedural gaps across both groups may suggest that such gaps are generally more manageable, this interpretation should be treated cautiously. Rather than viewing procedural gaps as uniformly simple, the literature suggests that the cognitive demands associated with procedural knowledge vary along a continuum depending on the order and complexity of the procedures involved (Stevenson, 1994; De Jong and Ferguson-Hessler, 1996; McCormick, 1997). From a cognitive-load perspective, procedural gaps often involve tasks with relatively low element interactivity, such as following known algorithms or performing experimentally observable steps, which tend to impose a lower intrinsic cognitive load (Sweller, 1988, 2010; Paas *et al.*, 2003). However, higher-order procedural gaps that require strategic control, monitoring, or coordination of multiple variables involve metacognitive processes that increase their cognitive demand beyond routine procedural work (Stevenson, 1994; McCormick, 1997). Compared to conceptual and epistemic gaps, which demand the integration of multiple abstract constructs and epistemic justifications, procedural gaps may be more likely to be resolved through stepwise reasoning and shared observation.

The procedural gaps addressed by both groups, including determining how to incorporate vapor pressure into gas-law calculations, converting pressure units when computing $P_{gas} = P_h + P_{atm}$, or deciding whether the syringe piston should be pushed or pulled when measuring gas volume, required coordinating a limited number of interacting elements that could be processed sequentially, thereby representing low element interactivity (Sweller, 2010; Ngu and Phan, 2016). In Group 1, for example, students collaboratively traced how vapor pressure should be subtracted from the total pressure by recalling that gases collected over water exert additional pressure due to vapor. In Group 2's procedural gap, students reached a brief consensus that pulling the syringe piston was easier because it produced the same manometric level difference as pushing, but they did not further articulate why this observation fit within the Boyle's law framework. These procedural gaps appeared to keep cognitive demands within working memory limits, thereby allowing the groups to make progress toward explanation building (Paas *et al.*, 2003; Ngu and Phan, 2016).

By contrast, the conceptual and epistemic gaps that Group 2 could not resolve involved higher element interactivity, requiring students to coordinate multiple abstract constructs such as the particulate nature of matter, the pressure–volume relationship, and the epistemic justification of results, which may have placed heavier demands on working memory and hindered sustained sensemaking (Sweller, 1988, 2010).

Conceptual gaps arise when students struggle to explain a phenomenon using their prior knowledge, often due to incomplete or contradictory understandings. Conceptual understanding demands recognizing relationships between principles and representations rather than merely applying algorithmic steps (Braithwaite and Sprague, 2021). For instance, the group's difficulty in determining whether pushing the syringe added air or merely changed the pressure or volume reflected a conceptual gap: students were unable to link the macroscopic manipulation of the syringe to the underlying particulate model of gases and the pressure–volume relationship. This difficulty illustrates a breakdown between procedural execution and conceptual understanding, where the physical act of manipulating equipment did not translate into an understanding of the chemical phenomenon. This finding aligns with chemistry education research, which emphasizes that meaningful understanding emerges when students integrate procedural fluency with conceptual insight, rather than treating laboratory tasks as algorithmic exercises (Pontigon and Talanquer, 2025).

Epistemic gaps, on the other hand, reflect uncertainty about how scientific knowledge is constructed, justified, and evaluated. In this study, an illustrative epistemic gap emerged when the experimental data did not align with Boyle's law. The students repeatedly cycled back through their observations, posing vexing questions such as "Why does P increase as V increases?", "Doesn't the syringe only change volume?", and "How can pressure increase as volume increases?" These persistent vexing questions revealed their struggle to reconcile empirical results with theoretical expectations, a hallmark of epistemic uncertainty, as students questioned not only what was happening but also how valid their data and reasoning were. However, despite these repeated attempts to make sense of the discrepancy, the group ultimately withdrew from the discussion, leaving the epistemic gap unresolved. Such epistemic gaps require not only disciplinary but also metacognitive and epistemic resources, competencies that many students may lack, thus increasing cognitive load (Chen, 2025).

It should not be inferred, however, that conceptual and epistemic gaps are inherently unresolvable. Rather, their resolution seems to depend on whether the cognitive demands of the task stay within learners' working memory capacity and on whether students are able to sustain explanation-building efforts while working through those demands (McCormick, 1997; Sweller, 2010; Ngu and Phan, 2016). In the present study, the high element interactivity of the task, together with limited timely instructional support during task engagement, may have exceeded these

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boundaries, thereby limiting Group 2's capacity to resolve such gaps. These difficulties are consistent with critiques that traditional laboratory instruction, which often prioritizes procedural correctness and factual recall, limits students' opportunities to engage in authentic sensemaking and develop epistemic awareness (National Research Council [NRC], 2012). Such limitations may also exacerbate inequities, as differences in students' opportunities and capacities to engage with chemical ideas can lead some to disengage while others persist (Nennig *et al.*, 2023).

The findings also underscored that students' epistemic emotions were closely intertwined with their sensemaking trajectories throughout the laboratory activity. When encountering the task, both groups experienced positive activating emotions, such as curiosity and surprise, which are known to foster cognitive engagement and exploratory behaviors (Vogl *et al.*, 2020; Pekrun *et al.*, 2023). However, notable differences emerged in their emotional dynamics during the designing the experiment stage. Although both groups experienced confusion at this point, in Group 1, it co-occurred with positive activating emotions, suggesting that confusion functioned as a productive state (D'Mello and Graesser, 2012). In contrast, Group 2 experienced confusion in conjunction with negative emotions such as anxiety and boredom, which are known to hinder problem-solving and diminish persistence (D'Mello and Graesser, 2012; Arguel *et al.*, 2019). The dominance of negative emotions, such as frustration and boredom, toward the end of the activity in Group 2 may have compounded cognitive demands and limited the group's ability to effectively address conceptual and epistemic knowledge gaps, thereby contributing to its disengaging sensemaking trajectory.

These results are consistent with D'Mello and Graesser's (2012) model of cognitive disequilibrium, which highlights confusion as a potentially productive emotion when successfully managed. Group 1's confusion, stemming from procedural gaps, was resolved through collaborative reasoning and co-occurred with positive activating emotions. This trajectory mirrors what D'Mello and Graesser term "productive confusion," where learners engage in effortful problem-solving to overcome impasses and restore cognitive equilibrium. Conversely, Group 2's experience was more consistent with "hopeless confusion," as the group struggled with conceptual and epistemic gaps, which are types of gaps that demand conceptual restructuring and metacognitive strategies, and which they were unable to navigate. The persistent confusion, coupled with negative activating emotions such as frustration and a deactivating emotion, boredom, was closely associated with the group's overall disengaging sensemaking trajectory. This pattern aligns with findings by Vilhunen *et al.* (2021), who reported that the practical phases of laboratory work, involving hands-on investigation, tended to evoke lower levels of anxiety, confusion, and frustration, whereas computational phases such as data analysis and model development elicited significantly higher levels of these negatively valenced emotions. Taken together, these results suggest that as cognitive demands increase, learners may become more vulnerable to unproductive forms of confusion, particularly when persistent knowledge gaps are accompanied by increasingly negative epistemic emotions. This interpretation is consistent with the view that cognitive and emotional dynamics in laboratory work are closely intertwined, such that heavier cognitive demands may increase the likelihood that confusion gives way to frustration, boredom, and disengagement.

Conclusions and implications

The present study characterizes student sensemaking as a dynamic process that can unfold along sustained or disengaging trajectories, thereby extending the "epistemic game" framework, which recognizes that students may end inquiry efforts prematurely (Odden and Russ, 2018). While prior research has extensively documented successful sensemaking and explanatory resolution (Hunter *et al.*, 2021; Ha *et al.*, 2024a, 2024b), identifying and modeling disengaging trajectories allows for a more detailed understanding of the conditions under which sensemaking efforts are maintained or discontinued in the laboratory. By focusing on the interplay of cognitive and affective shifts across time, these findings offer a lens to interpret how students' engagement is sustained, challenged, or begins to diminish within the specific context of undergraduate chemistry laboratory work. While this study does not evaluate the effectiveness of specific instructional strategies, the identification of sustained and disengaging trajectories provides insight into the moments during laboratory work when instructional support may be particularly relevant. Prior research indicates that timely support, such as encouraging students to reason through the problem, prompting them to explain their thinking, and providing targeted feedback when they are stuck, can help learners use confusion productively (VanLehn *et al.*, 2003; D'Mello and Graesser, 2012).

An important implication of the present study is that not all instances in which students encounter knowledge gaps should be interpreted in the same way. Some may reflect continued explanation building, whereas others may signal that students are beginning to disengage from sensemaking. Distinguishing between these patterns may help instructors respond more sensitively to students' cognitive and emotional needs. The findings further suggest that instructors may benefit from considering the nature of a student's knowledge gap, since different types of gaps may influence students' sensemaking in different ways.

Epistemic emotions may also function as useful indicators of how students are progressing through sensemaking. In particular, shifts from confusion toward frustration or boredom may signal that students are no longer productively working through the knowledge gap they have encountered. Future research could build on these findings by examining how different forms of instructional support may relate to students' navigation of knowledge gaps and epistemic emotions across sustained and disengaging sensemaking trajectories.

In addition to implications for instructional support during laboratory tasks, the findings also point to a broader curricular

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and instructional consideration. Many students enter inquiry-based laboratory settings with prior exposure to predominantly traditional, procedure-oriented instructional formats (NRC, 2012; Nennig *et al.*, 2023). In the present context, participants' prior General Chemistry Laboratory I course was conducted primarily in a traditional, procedure-oriented format rather than an inquiry-based format. Such educational backgrounds may limit students' familiarity with epistemic reasoning and reflective practices, which can constrain their ability to engage productively with knowledge gaps during inquiry-based laboratory work. Increasing students' exposure to learning environments that encourage them to question, interpret, and justify data, rather than merely follow prescribed procedures, could help them develop a deeper understanding of how scientific knowledge is constructed and validated. Over time, such experiences may strengthen students' capacity to integrate procedural fluency with conceptual understanding and epistemic reflection, thereby supporting more sustained sensemaking in chemistry laboratories. Future research could examine these links more directly by investigating how students' prior laboratory experiences relate to sustained *versus* disengaging sensemaking trajectories.

Limitations

The data for this study were drawn from a larger project investigating students' sensemaking processes in an inquiry-based laboratory environment. Although the broader project included several laboratory activities, within the subset of groups working without small-group guidance, a comparable within-activity contrast between sustained and disengaging sensemaking trajectories was observed only in the activity exploring the pressure–volume relationship of gases. Consequently, the present study is limited to Boyle's law activity and the two groups that exhibited these contrasting sensemaking trajectories.

Although a pilot study was conducted to refine the procedures for identifying students' epistemic emotions, these emotions were ultimately determined based on students' self-reports. This reliance on self-reported data represents a limitation, as such data may not fully capture the complexity or situational variability of students' emotional experiences during sensemaking.

Another limitation concerns the timing of emotion data collection. Because each laboratory session lasted two class hours, collecting emotion data at multiple points during the activity was avoided to prevent disrupting students' engagement and concentration. Therefore, students were asked to record their emotions retrospectively in emotion diaries at the end of the activity, rather than immediately after each stage.

Author contributions

Z. D. K. G. contributed to funding acquisition, conceptualization, and methodology, conducted the investigation, formal analysis, and data curation, and led the writing process and project administration. N. T. O. contributed to the investigation, data curation, formal analysis, visualization, and writing. S. G. supported the investigation, data curation, formal analysis, visualization, and writing. H. K. performed the investigation, data curation, and formal analysis and contributed to the visualization and writing of the manuscript. B. I. contributed to the investigation, formal analysis, and writing. H. T. contributed to the investigation, formal analysis, and writing. F. E. contributed to the investigation, formal analysis, and writing. S. N. Y. contributed to the investigation, formal analysis, and writing. D. D. assisted with the investigation, formal analysis, and drafting of the original manuscript.

Conflicts of interest

There are no conflicts to declare.

Data availability

Due to ethical and confidentiality restrictions, the qualitative data generated in this study cannot be shared publicly. Ethical approval was granted by the university's review board (Approval date: 24 December 2024; Decision No. 21).

Supplementary information (SI) includes details of the broader project structure, the Boyle's law activity sheet, the epistemic emotion diary, and the codebook used in the analysis. See DOI: https://doi.org/10.1039/d5rp00443h.

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