SUPPLEMENTARY INFORMATION

Undergraduate Chemistry Students' Sensemaking in a Laboratory Setting: The Interplay of Knowledge Gaps and Epistemic Emotions

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Broader Project Structure and Instructional Implementation

The broader project was conducted over a 15-week semester in the General Chemistry Laboratory II course during the spring semester of the 2024-2025 academic year. Students attended weekly two-hour laboratory sessions and worked in five heterogeneous groups of three to four students throughout the semester. Group heterogeneity was structured using students' GPAs, and students agreed to remain in their assigned groups across the semester.

As part of the broader project, the research team met weekly beginning one year prior to implementation. During this preparatory period, an extensive review of the relevant literature was undertaken, instructional activities grounded in chemical thinking were designed, and pilot implementations were carried out in the General Chemistry Laboratory II course. Insights gained from the pilot study informed the systematic revision of both the instructional activities and the data collection instruments. In addition, the data generated during the pilot phase were examined in depth to develop and refine the analytical framework used in the present study.

Chemical thinking activities provide an effective learning environment that supports sensemaking (Sevian & Talanquer, 2014; Talanquer, 2018). By engaging in tasks such as analyzing, synthesizing, and transforming matter, students can connect theoretical knowledge with experimental practice and personal experience, allowing them to apply scientific perspectives to real-world problems. Thus, chemical thinking activities offer a particularly suitable context for fostering sensemaking. Students completed a total of 11 laboratory experiments during the semester. Six of these were redesigned by the research team with an emphasis on chemical thinking (Talanquer & Pollard, 2010): Crystallization, Stoichiometry, Boyle's law, Freezing Point Depression, Acid-Base Titration, and Fractional Crystallization. These six activities followed an inquiry-based approach and incorporated the Predict-Observe-Explain (POE) technique. The remaining five experiments were likewise implemented within an inquiry-based approach; however, students' sensemaking processes were not examined during those sessions in order to avoid imposing additional demands associated with the research process. In structuring the sequence of activities, particular attention was paid to ensuring that the six chemical thinking activities were not scheduled in consecutive weeks (see Table 1). Students completed these experiments after studying the related topics in the theoretical General Chemistry II course.

Within the six chemical thinking activities, three of the five groups received small-group guidance, whereas the other two groups completed the activities without ongoing small-group guidance. Because the broader project also examined the influence of small-group guidance, the groups working without ongoing small-group guidance were rotated weekly rather than assigning the same groups to this condition throughout the semester. This rotation was intended to avoid creating a perception of neglect among participants, to minimize additional affective load, and to support equitable learning opportunities. During the weeks when guidance was provided, the student groups were guided by five researchers from the research team. Each guided group worked with the same researcher across all guidance sessions; that is, each researcher was assigned to a specific student group (see Table 1). Small-group guidance refers to facilitative support provided during chemical thinking activities. During the sessions in which guidance was provided, the guides asked probing questions, prompted students to articulate and justify their reasoning, and encouraged them to connect their observations with chemical concepts, while avoiding direct explanation or instruction.

Table 1. The Content of the Course and the Distribution of Small-Group Guidance During the Related Experiments

Week	Content	Small-Group Guidance*				
		Group1	Group2	Group3	Group4	Group5
1	Information on the Course Objectives, Content, and Implementation					
2	Crystallization	√	X	X	√	√
3	Stoichiometry	√	√	√	X	X
4	Reaction Rate					
5**	Boyle's Law	X	X	√	√	√
6	Heat of Reaction					

7	Strong Acid–Base Titration					
8	Determination of the Molar Mass of a Metal					
9	Midterm Week					
10	Determination of Structure Through Titration	X	√	√	X	√
11	Chemical Equilibrium					
12	Public Holiday					
13	Fractional Crystallization	X	X	√	√	√
14	Freezing Point Depression	√	√	X	√	X
15	General Evaluation					

* The √ symbol indicates that the relevant groups received small-group guidance from the same guide during the specified week, whereas the X symbol indicates that no small-group guidance was provided. No data were collected during weeks in which these symbols were absent.

** The data reported in the current study consist of those collected from Group 1 and Group 2 during the Boyle's law experiment.

During all laboratory activities, the course instructor, who was also one of the researchers, was present in addition to the small-group guides. In the guided condition, the small-group guides interacted with students during task work to support their progress through the activity. Because the data were collected as part of a course and supporting students' attainment of the intended learning objectives was essential, the instructor provided brief conceptual explanations at the end of each activity to offer pedagogical closure and to support students in developing a coherent understanding of the key chemical ideas involved in the laboratory activity. These explanations were provided only after data collection for the activity had been completed so that they would not influence the data collection process. For groups working without ongoing small-group guidance, the instructor intervened only when necessary to maintain continuity of the activity and to address safety concerns, while avoiding any influence on the substance of group discussions. The instructor also reviewed the procedures designed by these groups for safety and approved only those considered safe to conduct. Thus, working without ongoing 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.

All group interactions were audio- and video-recorded to capture the sensemaking processes, and collaborative activity sheets were collected at the end of each session. Participants also completed individual emotion diaries to report the epistemic emotions they experienced.

Prior to research data collection, students received instruction on the nature and function of epistemic emotions and on how these differ from other emotions. Subsequently, they were shown a video of a chemistry experiment and were asked to identify the epistemic emotions they experienced at different stages of the experimental process. The epistemic emotions they reported were discussed in class to clarify and validate the corresponding epistemic emotion categories. In addition, during each laboratory session, students were provided with an information sheet on epistemic emotions as presented below. This preparation was intended to support consistent use of the emotion diary during subsequent hands-on laboratory work. For the present study, the Boyle's law activity was the third laboratory activity from which data were collected in the broader project. Accordingly, students had already completed the epistemic emotion diary twice prior to the Boyle's law activity, which helped familiarize them with the reporting procedure.

The following information sheet was provided to students during laboratory sessions to support consistent identification and reporting of epistemic emotions.

References

Sevian H. and Talanquer V., (2014), Rethinking chemistry: a learning progression on chemical thinking, *Chem. Educ. Res. Pract.,* **15**(1), 10–23, DOI: 10.1039/C3RP00111C.

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Information Sheet about Epistemic Emotions

Emotions related to knowledge production are referred to as epistemic. These emotions arise from the cognitive characteristics of task knowledge, such as how cognitive dissonance triggers surprise and curiosity. They are considered epistemic because they relate to the epistemic (knowledge-related or pertaining to learning and understanding) aspects of learning and cognitive activity.

A typical sequence of epistemic emotions caused by a cognitive problem includes:

(1) Surprise;

(2) If surprise is not resolved, Curiosity;

(3) Anxiety when a serious inconsistency disturbs existing cognitive schemas;

(4) Enjoyment when information is successfully reorganized to solve the problem; or

(5) Frustration when this seems impossible.

Epistemic emotions can be positive (pleasant emotions experienced by the individual) or negative (unpleasant emotions experienced by the individual).

Positive epistemic emotions: Enjoyment, Surprise, Curiosity, Contentment

Negative epistemic emotions: Confusion, Frustration, Anxiety, Boredom

Epistemic emotions can also be classified as activating (when the experienced emotion motivates the person to perform) or deactivating (when the experienced emotion discourages the person from performing).

Positive activating epistemic emotions: Enjoyment, Surprise, Curiosity

Positive deactivating epistemic emotions: Contentment

Negative activating epistemic emotions: Confusion, Frustration, Anxiety

Negative deactivating epistemic emotions: Boredom

Definitions and Differences of Epistemic Emotions

Positive Epistemic Emotions

Enjoyment: The pleasure experienced when solving a problem, gaining new knowledge, or accomplishing a task.

Surprise: The initial reaction that occurs when new information conflicts with prior knowledge. This emotion often marks the beginning of curiosity.

Curiosity: A strong desire to learn, fill a knowledge gap, resolve an inconsistency, or solve a problem.

Contentment: The satisfaction and relaxation that arise after solving a problem or completing a task.

Negative Epistemic Emotions

Confusion: Occurs when it is unclear how to fill a knowledge gap or resolve a cognitive inconsistency.

Anxiety: The feeling that arises when there is too much inconsistency between prior and new knowledge, deeply disturbing existing understanding.

Frustration: The negative feeling experienced when inconsistencies cannot be resolved, expected results are not achieved, or a problem cannot be solved.

Boredom: The emotion that occurs when inconsistencies between prior and new knowledge seem impossible to resolve, or when interest is lost.

Activating and Deactivating Epistemic Emotions

Activating emotions: Positive emotions such as *Enjoyment*, *Surprise*, and *Curiosity*, as well as negative ones like *Confusion*, *Frustration*, and *Anxiety*, are emotions that motivate a person to continue solving the problem or performing the task.

Deactivating emotions: Positive emotion, *Contentment*, and negative one, *Boredom*, are emotions that cause a person to lose interest in the problem or task.

Examples of Epistemic Emotions in a Chemistry Experiment

Experiment: Burning of a magnesium ribbon to form magnesium oxide (MgO).

Explanation: When magnesium reacts with oxygen, it produces a light so bright that it can temporarily blind you. This reaction forms a white powder, magnesium oxide (MgO).

Student task: Explain the cause of the bright light observed and the formation of the white powder product in the burning of magnesium.

- **Surprise:** Felt when seeing the bright light during the burning of the magnesium ribbon — for example, "I didn't expect a metal to emit such a bright light when burning."
- **Curiosity:** The desire to ask, "Why does this reaction emit such a bright light?"
- **Confusion:** Difficulty understanding why the reaction product is a white powder.
- **Enjoyment:** Pleasure experienced while interpreting their observations during the experiment.
- **Frustration:** When they cannot explain, with their existing knowledge, why the reaction emits bright light or produces a white powder.
- **Anxiety:** Worry arising from thoughts such as, "I can't explain why this reaction emits such bright light. Is my knowledge insufficient?"
- **Boredom:** Loss of interest because the results were as expected or because no explanation could be found.
- **Contentment:** The feeling of satisfaction and relaxation after finding the answers to the experiment's questions.

Reference

Pekrun R., (2006), The control-value theory of achievement emotions: assumptions, corollaries, and implications for educational research and practice, *Educ. Psychol. Rev*., **18**(4), 315–341, DOI: 10.1007/s10648-006-9029-9.

Boyle's law Activity

Natural gas technicians use a water-filled U-tube manometer to detect gas leaks.

Task

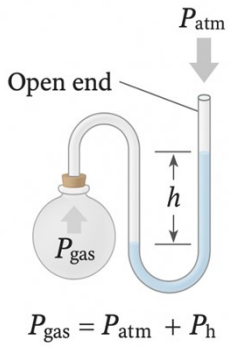
You are expected to design and conduct an experiment using a U-tube manometer and a syringe to demonstrate the relationship between gas pressure and volume, collect data, and produce a graph showing this relationship.

Background

For a fixed amount of gas at constant temperature, the relationship between volume and pressure is described by Boyle's law. In this activity, you will apply Boyle's law in practice.

An open-end manometer is a useful device for measuring gas pressures. The hydrostatic pressure (P_h) arising from the difference between the liquid levels in the manometer can be calculated from the height of the liquid column (h), the density of the liquid (ρ), and gravitational acceleration (g), according to the equation:

$P_h = h.\rho.g$



Reminder

The equation for hydrostatic pressure is derived from the formula of pressure P = F/A:

$P = F/A = m \cdot g/A = V \cdot \rho \cdot g/A = h \cdot A \cdot \rho \cdot g/A = h \cdot \rho \cdot g$

For example, if water is used as the liquid in the manometer and the hydrostatic pressure is to be expressed in millimeters of mercury (mmHg), the following relationship can be used:

$h_{water} \cdot \rho_{water} \cdot g = h_{Hg} \cdot \rho_{Hg} \cdot g$ (ρ_{water} = 1.00 g/cm³; ρ_{Hg} = 13.6 g/cm³)

$P\ (mmHg) = h_{water}(mm) \cdot 1.00/13.6$

Note: Assume the atmospheric pressure is 760 mmHg and the vapor pressure of water at 25 °C is 23.8 mmHg.

Designing the Experiment

Design an experiment to complete your task and describe your experimental method in detail.

Conducting the Experiment and Collecting Data

After obtaining approval from your instructor for your experimental design, conduct your experiment. Record your observations and data in this section.

Results of the Experiment

Using your pairs of pressure and volume data, plot a P (mmHg) – V (mL) graph and interpret your graph.

Interpretation of the Results

Does your data support Boyle's law? If not, what could be the sources of error in your experiment?

Epistemic Emotion Diary

Name-Surname:	**Date:**
Group Members:	**Experiment Name:**

The table below presents both positive and negative emotions that may help reveal the emotions you might experience during the experiment. Please consider the emotions listed in the table as you respond to the following questions. You may experience multiple emotions. For each emotion, please provide a separate explanation detailing the emotion itself and the reason for experiencing it.

Epistemic Emotions	
Anxiety	Curiosity
Boredom	Enjoyment
Confusion	Frustration
Contentment	Surprise

My Epistemic Emotions During the Experiment

The emotions I experienced during the experiment and the reasons for experiencing them, described for each of the categories listed below.

a. **Encountering the task:**

b. **Designing the experiment:**

c. **Conducting the experiment and collecting data:**

d. **Results of the experiment:**

e. **Interpretation of the results:**

Sensemaking Coding Framework

	Steps	Definitions	Key Features
Structural Components	**Step 0** Assembling a knowledge framework	Step 0 refers to the activation and organization of students' prior knowledge to construct an initial knowledge framework about the topic. This framework serves as a necessary precursor to sensemaking, as students do not yet perceive gaps or inconsistencies in their understanding until this initial framework has been assembled.	• Discussion or explanation drawing on students' prior knowledge. • May include references to everyday experiences or familiar phenomena. • Recalling relevant facts, events, or concepts from previous learning.
	Step 1 Noticing a gap or inconsistency	Step 1 refers to the moment when at least one student recognizes a gap or inconsistency in their understanding while attempting to articulate a phenomenon using their assembled knowledge framework. The emergence of these gaps or inconsistencies marks a transition towards the sensemaking frame, serving as the entry condition for the sensemaking epistemic game.	• Recognition or articulation of a perceived gap or inconsistency in understanding. • Expression of surprise or awareness of an unexpected outcome or situation. • Identification of anomalous data that conflict with prior knowledge, observation, or ideas.
	Step 2 Generating an explanation	In this step, students attempt to construct explanations to resolve the perceived gap or inconsistency. This process often involves proposing, revising, or rejecting explanations as they test and refine their ideas against evidence or reasoning. Students may generate several competing explanations for the same phenomenon before converging on one that appears coherent and satisfactory.	**Robust Explanation Building** • Engaging in collaborative discussions that build on one another's ideas. • Critiquing or questioning others' reasoning to strengthen emerging explanations. • Repeatedly articulating *vexing questions* that drive the refinement of ideas. *A vexing question (VQ) refers to a recurring question or statement that reflects students' attempts to make sense of a phenomenon when they are unable to form a coherent explanation based on their prior knowledge. Such questions typically emerge when learners experience gaps, inconsistencies, or conflicts between existing and new information. They evoke uncertainty, indecision, or cognitive tension within the group and thereby serve as catalysts for the sensemaking process (Haraldsrud & Odden, 2024; Odden & Russ, 2019).*

			Quality of Explanation • Articulating how or why a particular phenomenon occurs, linking underlying principles to observed outcomes. • Constructing explanations that include a clear claim supported by relevant evidence and justified through *reasoning*. *Claim-Evidence-Reasoning definition based on Haraldsrud & Odden (2024) and McNeill et al. (2006):* *Claim: A statement or conclusion that directly answers the focal question or describes the phenomenon under investigation.* *Evidence: Appropriate and sufficient scientific data, observations, or arguments that support the claim, rather than personal beliefs or opinions.* *Reasoning: The logical justification that connects the evidence to the claim, which can include relevant scientific principles, mechanisms, or theories.*
	Step 3 Resolution	The stage in which students construct a coherent explanation that resolves the previously identified gap or inconsistency, leading to a shared understanding where the phenomenon finally "makes sense".	• A final statement indicating the group's general consensus; although this consensus may not be scientifically accurate, it reflects a shared sense of resolution. • A plausible explanation is articulated that fills the gap in knowledge or resolves the identified inconsistency.

Successful Sensemaking: A process in which students activate and organize prior knowledge to construct an initial explanatory framework (Step 0), at least one student recognizes a gap or inconsistency in their understanding (Step 1), and students iteratively generate and refine explanations to address it (Step 2). The process culminates when the group reaches a shared and coherent resolution that fills the identified gap or resolves the inconsistency (Step 3).

Unsuccessful Sensemaking: Similar to successful sensemaking, Steps 0 and 1 are present as students activate and organize prior knowledge and recognize a gap or inconsistency. However, Step 2 is characterized by ineffective attempts to generate and refine explanations, and Step 3 is absent, as the group repeatedly cycles back to the same vexing questions without reaching a coherent resolution.

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