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General chemistry students' resource activation patterns in a titration curve interpretation task

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How students read graphical information in chemistry depends not only on what a graph displays but on which features they treat as meaningful and what knowledge those features activate. This study uses the cognitive resources perspective as framing to examine how undergraduate general chemistry students reason about titration curves in a preservative selection task involving juice stability and microbial growth. Twelve second-semester general chemistry students participated in think-aloud interviews while selecting a preservative based on graphical evidence. Analysis identified two distinct resource activation patterns. For six students, reasoning was organized around discrete pH values, drawing on part-for-whole and comparing resources productive in stoichiometric contexts. For five students, reasoning centered on slope and rate of change, with resistance-to-change resources linked functionally to preservation goals. One student activated both patterns. Although all approaches drew on productive existing knowledge and could yield correct selections, they reflected qualitatively different activation patterns. These findings indicate that variation in titration curve interpretation reflects differential activation of existing resources shaped by perceptual salience and task framing, with implications for how instruction might support students in activating slope- and resistance-based reasoning in graphical contexts.

Introduction

Graphs are central representational tools in chemistry, supporting explanation, prediction, and communication of relationships between variables. In general chemistry courses, students routinely encounter graphs such as titration curves, phase diagrams, and kinetic plots. A growing body of work documents that interpreting such graphs is not a uniform process: Students differ substantially in which features they treat as information-bearing, which knowledge those features activate, and how the activated knowledge links to disciplinary goals (Rodriguez *et al.*, 2020a; Talanquer, 2022; Rodriguez and Jones, 2024). Students who interpret the same graph differently often draw on productive, discipline-relevant resources in both cases; what differs is which resources are recruited, how they are coordinated, and what aspects of the representation trigger their activation.

The cognitive resources perspective (Hammer, 2000; Hammer *et al.*, 2005) offers a framework for characterizing this variation. Rather than treating student reasoning as correct or incorrect knowledge application, it asks which knowledge elements are activated, how they are linked, and under what conditions. Two factors jointly shape activation. First, which features of a graph students treat as information-bearing, a perceptual-conceptual process characterized at fine grain by the graphical forms construct (Rodriguez *et al.*, 2020a), determines which resources are available to be recruited. Second, how students frame the evidential demands of the task, in the epistemological sense developed by Hammer and colleagues (2005), determines which of those resources are taken up as relevant and how they are organized into a reasoning chain. Instructional emphasis, prior experience, and the perceptual salience of representational features shape both (Planinic *et al.*, 2013; Ivanjek *et al.*, 2016; Talanquer, 2022). The result is that the same graph can prompt fundamentally different reasoning from different students, not because they differ in underlying knowledge, but because different features of the situation activate different resources and frame their relevance differently.

Titration curves present a particularly rich case for examining this context sensitivity. Such curves contain multiple types of potentially informative features, for instance, discrete values such as equivalence points and starting pH, as well as rate-based features such as slope and curvature. Interpreting buffered regions requires attending to how the system responds across intervals rather than at isolated points. Yet prior work suggests that students do not always treat rate-based features of titration curves as informative (Bowe *et al.*, 2025), and that which graphical features activate which knowledge

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elements depends heavily on task context and framing (Rodriguez *et al.*, 2020a, 2020b; Rodriguez and Jones, 2024), raising the question of what conditions support slope- and resistance-based reasoning in chemistry graph interpretation. The present study uses the cognitive resources perspective (Hammer, 2000; Hammer *et al.*, 2005) as framing to examine how undergraduate general chemistry students interpret titration curves in the context of a preservative selection task involving juice stability and microbial growth. By analyzing variation in resource activation patterns across students interpreting the same set of curves, the study investigates how graphical features and contextual framing relate to the reasoning pathways students construct, and why the same visual display can activate fundamentally different knowledge elements for different students.

Literature background

What shapes how students read graphs: features, framing, and knowledge activation

Interpreting graphs in disciplinary contexts requires more than extracting values; it involves coordinating visual features with representational conventions and domain knowledge (Roth and Bowen, 2001; Kozma and Russell, 2005). A consistent finding across research in mathematics, science, and chemistry education is that students' interpretations vary depending on which graphical features they treat as salient and how they construe those features as meaningful within a given context (Even, 1990; Moschkovich *et al.*, 1993; Moore and Thompson, 2015). This variation is not well explained by accounts that attribute interpretive difficulties to the presence or absence of correct conceptions. Instead, a growing body of work suggests that graph interpretation reflects the context-sensitive activation of fine-grained knowledge elements, resources that may be available to a student in one setting but go un-activated in another.

One dimension of this context sensitivity is disciplinary framing. Planinic *et al.* (2013) administered isomorphic graph problems, matched in mathematical structure but situated in mathematics, physics, and everyday contexts, to 385 first-year university students, finding that problems involving context were consistently more difficult than their direct mathematical equivalents, and that slope appeared to be better understood than area under a graph across all three domains. Ivanjek *et al.* (2016) analyzed the reasoning strategies students used on the same parallel tasks, providing a mechanism-level account of why context changed performance. In physics contexts, formula-based approaches were the dominant strategy, with students frequently applying incorrect formulas even on qualitative tasks where calculation was not required. On mathematically identical everyday-context problems, students generated a wider variety of strategies, including rise-over-run reasoning and informal comparison of change across intervals, because without ready-made formulas to deploy they were free to mobilize other available resources. Slope-height confusion was documented across all three domains but occurred more frequently in physics than in mathematics, underscoring that the activation of particular reasoning patterns depended on task framing rather than on fixed deficits in graphical knowledge. Together, these studies establish that disciplinary framing does not merely select among strategies but can be associated with students not drawing on reasoning they demonstrate successfully in other contexts.

A second dimension concerns the structural features of representations themselves. Talanquer (2022) argued that chemical representations vary along four interrelated dimensions: iconicity; quantitativeness; granularity; and dimensionality, each of which shapes the reasoning demands students encounter. A central concern is the distinction between explicit and implicit features: Because novice learners tend to rely on heuristic reasoning processes, they disproportionately attend to perceptually salient features while overlooking implicit attributes that may be more conceptually central. In graphical representations, for instance, students may judge a variable's rate of change based on its absolute value rather than the slope at that point, substituting an explicit, easily read feature for an implicit one that requires interpretation.

Perceptual engagement with salient graphical features can reinforce rather than remedy surface-level processing when students lack the framing needed to interpret what those features signify (Talanquer, 2022). However, identifying that learners prioritize salient features does not yet characterize what happens when particular features capture attention, that is, which knowledge elements activate in response to specific graphical cues, and why the same display might prompt fundamentally different reasoning depending on which features a student treats as informative.

Rodriguez *et al.* (2020a) introduced the construct of *graphical forms* to characterize this act of meaning-assignment: a graphical form pairs a *registration*, a structural feature or region of a graph that an individual attends to, with a *conceptual schema*, the intuitive mathematical idea assigned to it. Among the graphical forms identified across disciplinary contexts are *steepness as rate* (interpreting relative slope magnitude as information about rate of change), *straight means constant* (associating a linear region with stable, unchanging behavior), and *curve means change* (associating curvature with a rate that is itself changing). Rodriguez *et al.* (2020a) demonstrate that these forms are domain-general: the same intuitive ideas appear in biology, physics, calculus, and chemistry textbook contexts, which suggests they function as transferable resources that can be cued by structural features of a graph independent of disciplinary framing. Whether a student brings such a form to bear on a particular graph depends on which registrations they treat as meaningful.

Rodriguez and Jones (2024) extended this perspective by cataloging 26 graphical forms that students used when interpreting graphs across physical scenarios, demonstrating that students bring a diverse repertoire of intuitive knowledge to graphical activity, with the specific forms activated depending on the features of the task and the graphical patterns encountered. These studies collectively establish the *what* of graphical form activation (which forms exist and when they appear) but leave open the question of *how* a given form structures subsequent reasoning and which knowledge elements it brings to bear.

Rodriguez *et al.* (2020b) take up this question in a chemistry context, using coordination class theory to investigate how general chemistry students interpreted frequency distribution graphs. Their analysis revealed that two distinct readout strategies, viewing the graph as a distribution *versus* viewing it as a process, shaped which knowledge elements activated and, consequently, whether students could draw productive inferences. Students who adopted a distribution reading strategy recognized that molecular values vary and reasoned about how temperature changes would shift the distribution; students who adopted a process reading applied covariational reasoning, tracing how y changed with x and constructing causal narratives. Critically, nearly all students activated the idea that molecular values vary when reasoning about the same system without a graph, but students in the process group did not activate these resources when confronted with the graphical representation, highlighting that the issue was not an absence of productive knowledge but the context-sensitive nature of its activation.

Across this body of work, graph interpretation emerges as dependent on the interaction among representational features, task framing, and prior experience rather than solely on the correctness of underlying concepts (Planinic *et al.*, 2013; Ivanjek *et al.*, 2016). Broader scholarship on graphing competencies converges on the disciplinary embeddedness of these practices, emphasizing that graph interpretation is learned within disciplinary contexts and that prior knowledge shapes what inferences students draw from a given display (Gardner *et al.*, 2024).

The present study extends this line of research by examining how undergraduate chemistry students interpret titration curves in a preservation context, focusing on patterns of resource activation associated with the visual and contextual features of the task. The graphical forms construct and the cognitive resources perspective operate at different but complementary grain sizes, and the present study draws on both. Graphical forms are elemental knowledge pairings: each form specifies a registration, the structural feature of a graph that an individual treats as meaningful, and a conceptual schema, the intuitive idea assigned to it. They characterize fine-grained perceptual-conceptual events, the moment at which a particular curve feature activates a particular interpretive schema. Resource activation patterns, by contrast, operate at a broader grain. They describe which collections of resources are recruited across a reasoning episode, how those resources link together into functional chains, and what kind of inferential work the chain as a whole performs. In this study, graphical forms such as *smaller slope means more resistance to change* are among the elemental resources that students activate; point-based and resistance-based reasoning are the broader patterns into which those elements are organized. Distinguishing these grain sizes helps clarify what varies across students: not simply whether individual knowledge elements are present, but which elements activate, which registrations trigger them, and how the resulting resources link to one another and to preservation function.

Titration curve interpretation and buffer reasoning

A titration curve represents how the pH of a solution changes as titrant is incrementally added. Interpreting such curves requires coordinating graphical features, such as regions of shallow or steep change, with underlying acid–base processes. In the context of buffering, this coordination is particularly demanding: understanding depends on recognizing resistance to pH change, which is reflected graphically in regions where incremental additions produce relatively small changes in pH. Reasoning about buffering therefore involves attending not only to discrete values such as equivalence points but to how the system responds across intervals. Yet which of these features students treat as informative, and which knowledge elements those features activate, may vary depending on representational context and task framing.

Research on titration interpretation suggests this variation is substantial. Sheppard (2006) examined sixteen high school students' interpretations of a strong acid-strong base titration curve produced in real time using a computer-interfaced pH probe. Half of the students predicted a linear decline in pH, consistent with treating pH as a measure of the degree of acidity. When confronted with the actual sigmoidal curve, students struggled to account for its features: In the flat region, about half claimed the reaction had not yet started; at the steep transition, students invoked the reaction "suddenly occurring" rather than linking the pH change to near-equal concentrations of H^+ and OH^-. Notably, students' explanations during the titration task differed from the accounts of neutralization they had given in earlier interview tasks, suggesting that the graphical context itself elicited different reasoning rather than simply revealing stable conceptions.

A parallel pattern appears in research on buffer understanding, where the disconnect occurs not between graphical and verbal contexts but between functional conceptual knowledge and symbolic problem-solving. Orgill and Sutherland (2008), working from a misconceptions framework, found that undergraduate students across three course levels could articulate what buffers do but treated the Henderson–Hasselbalch equation as a self-contained procedure rather than as an expression of an underlying equilibrium, with upper-level students showing greater flexibility only because they could approach problems through multiple pathways. Reframed through a resources lens, these findings suggest that students possess relevant buffer knowledge but do not activate it consistently across representational contexts, a pattern that recurs in more recent work explicitly designed around resource activation.

Sheppard and Bauer (2023) examined how twelve second-semester general chemistry students approached three scaffolded conceptual buffer question sets and identified three levels of resource activation: *Surface Features*, in which students relied on readily accessible heuristics; *Building Connections*, in which students began linking resources such as proton transfer with conjugate pairing; and I*nterconnected*, in which students coordinated multiple resources into integrated explanations. Critically, activation was neither uniform nor stable: a given student's level often shifted across question sets, and resources that were productive in one context sometimes failed to activate in the next. These findings suggest that the challenge of buffer reasoning lies not in the absence of relevant knowledge but in the context-sensitive activation and coordination of resources across shifting problem demands.

Recent work extends this perspective to graphical interpretation of titration curves specifically. Bowe *et al.* (2025) examined how a first-year biochemistry student, selected from sixteen participants because she uniquely integrated ideas from biology, mathematics, and chemistry, visually segmented a strong acid-strong base titration curve into three regions based on slope and associated each region with different disciplinary resources. The flat regions activated mathematical graphical forms such as *straight means constant rate*; the steep region activated chemistry lab experience and a biology analogy to exponential growth. However, the shape-based approach limited the student's attention to incremental covariation within regions: She characterized each chunk's average behavior but did not track how pH covaried with volume across the interval. These findings suggest that attending to graph shapes as static objects, rather than as representations of covarying quantities (Moore and Thompson, 2015), can constrain which resources are brought to bear and how information is extracted.

Across this body of work, a consistent picture emerges: students bring relevant knowledge to titration curve interpretation, but which knowledge elements activate depends on which graphical features capture attention and how the task frames what counts as relevant information. Prior research has characterized these activation patterns in the context of scaffolded buffer problems (Sheppard and Bauer, 2023) and single-student case analyses of curve segmentation (Bowe *et al.*, 2025), but has not yet examined how variation in resource activation manifests when students interpret titration curves in an applied context that foregrounds system behavior, such as selecting a preservative, rather than identifying stoichiometric endpoints. The present study addresses this gap by analyzing how undergraduate general chemistry students reason about titration curves in a preservation scenario, investigating which resources activate, how those resources link together to produce reasoning, and what features of the task and its graphical representations cue different activation patterns.

Theoretical framework: the resources perspective

This study is grounded in the cognitive resources perspective (Hammer, 2000; Hammer *et al.*, 2005), a fine-grained constructivist perspective that models knowledge as composed of context-sensitive elements, that is resources, that activate dynamically in response to task features. Resources include intuitive knowledge drawn from everyday experience (*e.g.*, a sense that some systems resist perturbation, or that stronger agents produce greater effects) as well as knowledge compiled through prior instruction (*e.g.*, associating equivalence points with stoichiometric calculations). These elements are not inherently correct or incorrect; their productivity depends on whether they are activated in contexts where they support useful reasoning. This view aligns with earlier work emphasizing the fragmented and context-sensitive nature of intuitive knowledge (diSessa, 1993) and its application to chemistry learning (Taber and García-Franco, 2010). Importantly, the cognitive resources perspective requires researchers to make explicit what counts as a "resource" in a given study, since the term can be operationalized at varying grain sizes: from broad concept projections to fine-grained distributed elements and p-prims, with consequences for the scope of claims and instructional implications (Rodriguez, 2024). Our operationalization is described in the Data analysis section.

A central implication of this framework is that variation in student reasoning is expected rather than anomalous. The same student may activate different resources in response to differences in task framing, perceptual salience, or representational features (Hammer and Elby, 2003), and learning involves refining the conditions under which resources activate and strengthening productive linkages among them rather than replacing incorrect ideas wholesale (Hammer, 2000; Hammer *et al.*, 2005). Accordingly, the analytic focus shifts from asking what students know to examining which resources activate, what features of a task cue those resources, and how activated resources link together into functional reasoning networks. This last dimension, how resources connect, is particularly important, because the same resource may participate in productive reasoning in one network and unproductive reasoning in another, depending on what it is linked to and what role it plays.

This framing shapes the analytic approach of the present study. Rather than evaluating whether students possess correct conceptions of buffering, the analysis examines which knowledge elements activate when students interpret titration curves in a preservation context, what features of the graphs and the task cue those activations, and how activated resources link together to produce reasoning about preservative function. Because perceptual features such as discrete points, slope, and curvature may cue different intuitive resources depending on prior instructional emphasis and task framing (Ivanjek *et al.*, 2016; Bowe *et al.*, 2025), a resources perspective predicts that the same set of titration curves may activate fundamentally different knowledge elements for different students, a prediction the present study is designed to examine.

Research questions

This study examines how undergraduate general chemistry students reason about titration curves in the context of selecting a preservative for juice, a task requiring buffer reasoning. Two research questions guide the analysis:

1. What resource activation patterns do students exhibit when interpreting titration curves in a preservation context, and how do activated resources link together to produce preservative selection decisions?

2. What contextual features of the task influence which resources students activate?

In particular, we investigate which resources students bring to bear when interpreting curve shapes, how students link those resources together into functional reasoning pathways, and what features of the task and representation shape which resources students draw on. This approach foregrounds which productive knowledge elements students bring to the task and how they activate in this context, suggesting instructional approaches that support students in activating and coordinating existing knowledge rather than replacing misconceptions with correct conceptions.

Addressing these questions contributes to the field in two related ways. Theoretically, the study provides an account of how contextual and perceptual features of a specific chemistry representation interact with students' existing knowledge to produce variation in reasoning, extending cognitive resources perspective analyses from physics contexts into chemistry graph interpretation, and from the single-student case analysis of Bowe *et al.* (2025) to comparative cross-student analysis. Practically, this account reframes the instructional challenge: Rather than identifying what students do not know about buffering, it clarifies which features of tasks and representations are associated with productive resource activation, pointing toward design principles for titration curve activities that support students in activating and coordinating knowledge they already possess.

Methods

Participants and setting

Twelve students (P1–P12) enrolled in a second-semester general chemistry course at a large public university participated in individual think-aloud interviews. All participants had completed the first semester of general chemistry and were currently enrolled in the second semester. The course used an active-learning, flipped pedagogical approach and an open-source textbook following a traditional organization of material. The curriculum explicitly addressed acid–base equilibria and buffer systems through activities requiring students to reason at molecular and macroscopic levels and to interpret multiple representations including titration curves. Recruitment continued until no new resource activation patterns were emerging across successive interviews, consistent with the principle of thematic saturation in qualitative inquiry (Creswell and Poth, 2018). The specific instructional emphasis placed on different graphical features of titration curves, for instance, the relative attention devoted to equivalence points *versus* buffering regions, was not systematically documented as part of this study. Interpretive claims in the Results and Discussion about the role of prior instructional experience are therefore speculative, offered as plausible contextual explanations consistent with the data rather than as documented accounts of what these particular students were taught.

Ethical considerations

Participants volunteered in response to recruitment announcements in their course. All participants provided informed consent, and the study was approved by the university's Institutional Review Board. Participants received compensation for their time. To protect confidentiality, participants are identified by number (P1, P2, *etc.*) throughout this paper.

Interview task

Each participant completed an individual videotaped interview lasting approximately 45–60 minutes. Interviews followed a semi-structured protocol addressing acid–base reasoning through multiple tasks. This paper focuses on one task from the interview: a preservative selection problem requiring buffer reasoning in the context of graph interpretation (Fig. 1).

In this task, students were presented with a scenario describing juice preservation requirements: the preservative must maintain tartness (requiring acidic pH) while reducing microbial activity (most active in pH 6–8 range). Students were shown titration curves for five acid options (labelled by color: red, orange, yellow, green, blue) and asked to select the best preservative option. This context was chosen deliberately: the dual constraint structure of the task, maintaining acidic pH for tartness while suppressing microbial activity in the pH 6–8 range, foregrounds stable system behavior across a pH range rather than at a discrete point.

The titration curves showed pH (y-axis) *versus* volume of 0.1 M NaOH added (x-axis, 0–50 mL). Curves varied in starting pH, equivalence point location, and shape (slope/flatness). Yellow exhibited the flattest curve in the acidic pH range, indicating strong buffering capacity, while green, orange, and blue showed steeper slopes, indicating weaker buffering. Red

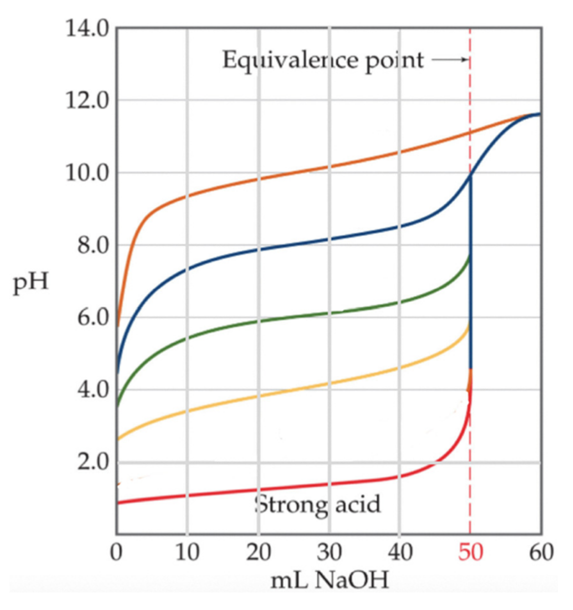

Fig. 1 Figure from preservative selection task. The prompt asked students to determine which colored curve would represent the best preservative for a juice. Students were told that microbial activity is highest in pH 6–8 and that tartness is desirable.

showed flatness but at excessively low pH (<2). A vertical line at 50 mL marked the equivalence point region where most curves converged. Successful preservative selection therefore requires perceiving curve shape and interpreting flatness as Smaller slope means more resistance to change, whether or not students use formal buffering terminology.

In the interview, students were asked to select a preservative and explain their reasoning aloud. The interviewer used non-directive follow-up prompts (''Can you say more about that?'' ''What are you thinking about?'') to encourage elaboration without suggesting particular reasoning pathways. When students made assertions without explanation, the interviewer probed for justification (*e.g.* ''Why does that matter?'' ''How did you decide that?''). If students' reasoning appeared incomplete or contradictory, the interviewer explicitly noted this and asked students to address it. This approach allowed observation of both students' initial resource activation patterns and how those patterns responded to challenges.

Data analysis

Video recordings were transcribed verbatim using the application Otter.ai. The unit of analysis was a student's complete response to an individual interview task, including follow-up exchanges initiated by the interviewer. Analysis focused on identifying which conceptual resources students activated when interpreting titration curves and how those resources were joined together to produce reasoning. We adopted a qualitative, interpretive approach informed by the cognitive resources perspective (Hammer, 2000; Hammer *et al.*, 2005).

Codes were developed from the data, informed by but not predetermined by the cognitive resources perspective, rather than applied from a fixed prior codebook. Analysis proceeded iteratively through three stages, with the full set of transcripts revisited after each stage as codes were refined.

In the first stage, we identified what students attended to in the graphs, that is which visual features they treated as meaningful. For example, some students focused on where curves ended, others tracked whether curves entered the pH 6–8 region at any point, and still others attended to curve steepness or flatness. This stage oriented the analysis toward perceptual engagement with the representation rather than evaluating correctness of attention.

In the second stage, we identified the reasoning resources students activated. A resource was considered activated when it was brought to bear as evidence in a student's reasoning, that is when it did observable work in justifying a claim or connecting a graphical feature to a conclusion, rather than merely being mentioned or potentially available. Following established resource-based analysis methods (Hammer, 2000; Wittmann, 2006) and consistent with the call to explicitly articulate what counts as a resource in a given study (Rodriguez, 2024), we examined student language for evidence of knowledge elements such as those in Tables 1–3. Resources were operationalized broadly, consistent with Hammer and Elby's (2003) account of the cognitive resources perspective as encompassing not only conceptual knowledge elements but also activity-type resources such as comparing and excluding, and perceptual strategies through which students extract information from representations; entries in the tables reflect this range. Resource identification focused on functional role rather than terminology. For instance, students describing curves as ''not changing much,'' ''staying flat,'' or ''resisting'' were coded as activating resistance resources even without using formal buffering language. Claims about resource availability should be understood as interpretive, not definitive.

In the third stage, we analyzed how resources linked together into functional reasoning pathways. Linking relationships were identified through discursive markers in the transcript, for instance, connectives such as ''so,'' ''because,'' ''that means,'' and ''which means,'' that indicated a student was using one idea as grounds for or consequence of another. We mapped which attended features appeared to cue which resources, how resources connected to one another, and whether these networks produced coherent reasoning about preservation function.

To support cross-case comparison and make coordination structures visible, we constructed resource graphs for each participant, informed by Wittmann's (2006) approach to visualizing knowledge coordination in student reasoning. Resource graphs for all twelve participants are provided as supplemental material, and the text references them at each case profile. Each graph displays the resources a student activated, organized into layers by resource type: registrations (perceptual readouts from the graph), graphical forms, conceptual resources, and epistemological framings where applicable. Resources are arranged chronologically from left to right within each layer, and directed arrows indicate which resources were linked to which, based on the discursive connectives identified in stage three.

Analysis was comparative across transcripts as well as iterative within them. Initial analysis of several transcripts generated preliminary categories and code definitions. Continued analysis of the full dataset prompted refinements to those definitions, tightening the criteria for specific codes and adjudicating edge cases where a student utterance was consistent with more than one resource. Two distinct patterns emerged through this process: point-based resource activation (attending to discrete pH values, activating comparison and ''stronger is better'' resources) and resistance-based resource activation (attending to slope and shape, producing resistance reasoning). Within each pattern, substantial variation existed in the sophistication and stability of reasoning under interviewer questioning.

Inter-rater reliability

To establish the reliability of the coding scheme, a second researcher independently coded a subset of the interview data (>20%) using the finalized code definitions. The two raters then compared coding decisions and discussed discrepancies, using disagreements to further refine code definitions and clarify boundary cases. Following these refinements, a second round of independent coding was conducted on the same

Table 1 Participant 4's activated resources

Resource	Definition
Part-for-whole	Treating the equivalence point as representative of the preservative's character
Excluding	Eliminating options whose equivalence points fall in problematic ranges
Lower pH means more tartness	Connecting lower pH values to more acidic/tart properties
Safety threshold	A harm-based constraint that eliminates options falling below a minimum level of acceptability, regardless of how well they satisfy other criteria.
Magnitude optimization	Selecting the option whose value is closest to a target reference point, rather than maximizing, minimizing, or simply crossing a threshold.

Table 2 Participant 7's activated resources

Resource	Definition
Comparing	Evaluating which curves have equivalence points in *versus* out of the 6–8 range
Part-for-whole	Treating the equivalence point as representative of the preservative's character
Stronger is better	Finding the most extreme value (lowest pH = strongest acid)
Lower pH means more tartness	Connecting lower pH values to more acidic/tart properties
Excluding	Eliminating options whose equivalence points fall in problematic ranges
Safety threshold	Applying a harm-based constraint that sets a lower bound on acceptable options
Analogy (orange juice)	A self-generated mapping from a familiar acidic food to the task context, used to ground the connection between low pH and tartness.

Table 3 Participant 6's activated resources (see SI for P6's resource graph)

Resource	Definition
Excluding	Eliminating curves that entered the problematic pH 6–8 range
Lower pH means more tartness	Linking acidity to tartness and microbial resistance
Slope as rate	Perceiving slope magnitude as information about rate of change
Comparing	Comparing total pH change over the full titration range
Smaller slope means more resistance to change	Connecting small total change to strong resistance
Resistance as opposition to pH change	The sense that a system pushes back against perturbation, such that a smaller change in pH in response to added base reflects a property of the system rather than an incidental outcome
Safety threshold	Applying a harm-based constraint that sets a lower bound on acceptable options
Analogy (digestive tract)	A self-generated mapping of the *x*-axis (volume of NaOH added) onto passage through the digestive tract, motivating attention to the full curve trajectory by framing each volume increment as a different physiological environment the preservative must withstand.

subset. Cohen's Kappa was calculated for this second round, yielding κ = 0.79, indicating substantial agreement between coders (Cohen, 1960).

Results

The analysis addresses two research questions: what resource activation patterns students exhibited and how activated resources linked together to produce preservative selection decisions (RQ1), and what contextual features of the task appeared to cue different activation patterns (RQ2). Findings for each question are presented in turn, drawing on semi-structured interview data from twelve second-semester general chemistry students. We begin with RQ1: What resource activation patterns do students exhibit, and how do activated resources link together to produce preservative selection decisions?

Overview of activation patterns

Across the twelve interviews, two qualitatively distinct patterns of resource activation emerged, organized around what graphical information students treated as meaningful. Six students (P3, P4, P5, P7, P9, P10) attended primarily to discrete pH values at specific curve locations and activated resources associated with point-based reasoning. Five students (P1, P2, P6, P8, P12) perceived and reasoned about how curves change, extracting rate and resistance information from curve shape. Although most of these students attended directly to slope, two (P6, P12) arrived at resistance reasoning through analogical reframing rather than direct slope perception, illustrating that rate-based perception is one route to resistance reasoning but not the only one. One student (P11) activated both patterns. Using the cognitive resources perspective (Hammer, 2000; Hammer *et al.*, 2005), we can specify what distinguishes these patterns: The nature of the resources activated when perceiving curve shape, and the ways in which those resources become functionally linked to preservation reasoning.

Pattern 1: point-based resource activation

Students who attended to discrete pH values at specific locations on curves typically activated resources that are highly productive in many chemistry contexts such as comparing values, identifying key points, applying acid–base knowledge. While such approaches enabled correct answer determination in some cases, in others they hindered accurate reasoning. As an example of point-based resource activation, consider the case of participant 4.

P4: equivalence point focus. P4 attended to equivalence points throughout the task, ultimately identifying the best answer (yellow curve). Early in the interview, P4 stated: "*the equivalence point…that's the point at which the preservative, there's no more left to react*." P4 could identify equivalence points and give a reasonable definition when prompted. However, when questioned as to why the endpoint was important in this context, P4 responded "*I'm not sure*" and was unable to elaborate further.

Despite this uncertainty, P4 proceeded to compare the pH of the curves' endpoints, noting: "the equivalence point for yellow is not between six and eight, it's lower. The equivalence point for green is between six and eight." They ruled out curves with an endpoint within the range of pH 6–8, which corresponded to higher microbial activity according to the prompt. They also used their knowledge of the association between lower pH and greater tartness to eliminate options whose equivalence point fell in the higher pH range.

P4's resource activation pattern included the following resources shown in Table 1 (see supplementary information for P4's full resource graph).

P4 could identify equivalence points accurately and apply elimination reasoning to arrive at a correct selection. However, P4 did not draw on graphical features associated with resistance to pH change, even when directly questioned as to what particular features could tell them. We interpret this as reflecting the context-specificity of resource activation: the equivalence point resources P4 deployed are productive and well-suited to stoichiometric tasks in which endpoints are the central feature of interest. In a task foregrounding system behavior across a pH range, different graphical features become relevant, and the resources for reading those features were not what this task context cued for P4. Next we consider the case of P7, who selected the red curve as the best option (incorrect).

P7: "Stronger is better" as selection logic. As with P4, we saw that P7's attention was oriented toward point values rather than curve behavior, and that they treated the equivalence point as representative of the preservative's character. P7 described their selection as follows: "*I chose the yellow one, because it had the lowest equivalence point, which then would make it the strongest acid, which would make the juice more tart.*" P7's discussion of their interpretation of the tartness constraint, "*the equivalence point that is the farthest away from six to eight*," suggests a "*part-for-whole*" resource, in which a single point is treated as representative of a substance's behavior. We observed this resource being applied alongside comparisons applied to point locations rather than trajectory or rate analysis.

When the interviewer pressed for the rationale behind their choice of yellow *versus* red, P7 waffled in their choice, initially saying "*I didn't pick red because it has such a low pH, I think it could maybe be harmful.*" However, a "*stronger is better*" resource (an instance of the "More A–More B" intuitive rule; diSessa, 1993; Stavy and Tirosh, 2000) applied to pH out, with P7 ultimately noting "*I would actually go with red because it would make it more tart and it's a stronger acid*." Here, a safety threshold resource surfaced briefly but did not sustain within P7's reasoning, with the "*stronger is better*" resource continuing to structure the selection.

P7's activated resources are shown in Table 2 (see supplementary information (SI) for P7's full resource graph).

Resistance-to-change resources were not in evidence in P7's reasoning. When asked explicitly about the role of curve shape in their reasoning, P7 stated: "*I don't think the shape of it matters, necessarily…I didn't really think about it*."

The idea of "*stronger is better*" can be highly productive in many preservation contexts (*e.g.*, concentrated substances resist dilution better), making it readily cued in preservation framings. In this context, however, its activation was associated with reduced attention to resistance-based features of the curves that would have supported buffer-relevant reasoning. P7 selected red, an incorrect choice.

In the next case, we examine the case of P3, who shared with P7 an orientation toward discrete values and a "*stronger is better*" logic, but added a layer of explicit temporal reasoning about system change, making it a case in which sophisticated dynamic thinking and point-based activation coexist.

P3: Sophisticated system dynamics without rate perception. P3 selected red and organized reasoning around both equivalence points and explicit temporal thinking about system change. Early in the task, P3 explained: "*If over time it becomes less and less tart, which means the pH will be increasing because it's becoming more basic, then we should add an acid or preservative with a low pH to maintain the tartness.*" This reflects a *replenishment* framing, which we considered a subtype of point-based reasoning in which the organizing evidence is still a discrete value (lowest pH), but the logic connecting that value to the selection criterion is temporal compensation rather than simple threshold comparison. P3 recognized that acidity would drift and that adding a low-pH preservative would restore it, coordinated with a "*stronger is better*" resource that treated acid strength as the relevant criterion for effectiveness: "*I think we should go with red, because red is a strong acid and has the lowest pH… preservatives, I think, are usually very strong.*"

What makes P3's case instructive is that the temporal reasoning is genuinely sophisticated. P3 tracked system change over time and reasoned about how to counteract it, but the epistemological structure remained point-based. For P4, P7, and most other point-based reasoning students, that value is the equivalence point location or starting pH, treated as representative of the preservative's character. For P3, that value is the lowest pH, treated as the measure of acid strength available to counteract drift. What distinguishes P3 is not the evidentiary basis but the logic connecting evidence to criterion: where other point-based students reason through threshold comparison or magnitude optimization, P3 reasons through temporal compensation. Curve shape and behavior across an interval played no evidentiary role. A preservative that resists pH change through buffering capacity and one that compensates for pH drift through acid strength are different solutions to the same problem, and P3's point-based framing made the latter the natural choice. Whether the flat regions of the curves were not perceived, were perceived but not taken up as relevant, or were simply not considered once P3's reasoning had generated a satisfactory answer, we cannot determine from this episode. What the case illustrates is that students can engage in dynamic chemical reasoning about system behavior without activating the shape-based resources that would connect buffering capacity to preservation function.

Pattern 2: resistance-based resource activation

Five students (P1, P2, P6, P8, P12) extracted fundamentally different information from the same graphs and, regardless of the perceptual route, all converged on resistance reasoning, connecting curve behavior to preservation function. These students attended to how curves change rather than to discrete values: rather than attending to discrete values at specific curve locations, they perceived and reasoned about how curves change across intervals. These students activated resistance-to-change resources and linked them functionally to preservation requirements, articulating their reasoning in varied ways and without necessarily using formal buffering terminology. The following profiles illustrate the range of ways this activation pattern was expressed through direct slope perception; a sixth case, P12, activated resistance resources through analogical reframing rather than slope reading and is presented in the contextual conditions section below.

P2: Resistance resources activated. In discussing the preservative task, P2 explained their selection of the yellow curve by saying: "It resisted the pH change the most… It changed pH the least amount when adding the same amount of acid… Because the slope is the least steep." We interpret this as reflecting a chain of linked resources. P2 attended to the relative steepness of the curves, perceiving that yellow had the least steep slope. In graphical forms terms (Rodriguez *et al.*, 2020a), P2's registration was the relative slope magnitude; the associated conceptual schema was resistance to change, specifically that a smaller slope indicated the system was opposing perturbation more effectively. This is the graphical form we term *smaller slope means more resistance to change*.

Finally, P2 linked resistance directly to preservation function, reasoning that the curve showing the least pH change would best maintain the acidic conditions required for preservation, connecting a graphical observation to a task goal without prompting.

Overall, P2 recognized the curve's shape as meaningful, connected it to how the system responds to perturbation, and applied that understanding to predict preservative effectiveness, buffer reasoning without buffer vocabulary. When asked about underlying chemistry concepts, P2 reflected: "*I guess it is kind of a chemistry concept, but I was just thinking about what's resisting the pH change*." This phrasing reveals something important: P2 initially viewed resistance as general reasoning rather than specifically chemical, only recognizing it as chemistry when prompted. This suggests the resistance resource may have come from other contexts, possibly physics (*e.g.* ideas such as friction resists motion), engineering (with ideas such as materials resist deformation), or everyday experience.

Next, we consider the case of P6, which extends this pattern by showing how resistance resources can be embedded within a broader, multiply-reinforcing reasoning structure, one in which the same conclusion is supported by independent pathways rather than a single chain.

P6: Multiple reinforcing pathways. P6 selected yellow through two independent pathways that converged on the same conclusion. The first was trajectory-based excluding: "*the yellow preservative does not hit a pH of six to eight at any point on the graph*." The second was rate-based: "*I noticed that the yellow and the green lines have the smallest slope. Actually, I would say yellow had the smallest change in pH from zero milliliters of NaOH to 50… it definitely has the smallest change, which means it's resisting the pH the most*." The rate pathway reflects the same resistance logic visible in P2's reasoning, here applied quantitatively: P6 attended to total pH change across the full titration range and used it as the basis for comparing resistance across curves. Table 3 shows Participant 6's activated resources.

The rate pathway engaged two graphical forms in the Rodriguez *et al.* (2020a) sense: slope as rate, in which curve steepness is perceived as information about rate of pH change, and smaller slope means more resistance, in which that rate reading is connected to a resistance schema. The trajectory-based pathway, by contrast, did not depend on these graphical forms; it required only that curves be tracked against a threshold, an operation that does not assign a rate or resistance schema to curve shape.

What distinguishes P6's case is the redundant structure of the reasoning. Trajectory-based excluding and rate comparison each independently supported yellow, so the conclusion did not depend on either pathway holding. This mutual reinforcement made P6's reasoning particularly robust and illustrates what coordinated resource activation looks like when multiple registrations are available and linked to the same functional concept.

Next we consider the case of P8, which extends the pattern in an important direction: Whereas P2 and P6 attended to the magnitude of slope as an indicator of resistance, P8 reasoned about how the rate of change itself changes, attending to the shape of the curve's trajectory as well as its overall steepness.

P8: Contrasting linear versus accelerating change. P8 selected the yellow curve and discussed curve shape as follows: "*You want something linear… because if it has, like, more of an* *increasing and increasing rate type of curve... your pH is changing very drastically at that rate. And you don't want that.*" Here, P8 activated multiple interconnected resources, including visual categorization of curve shape (distinguishing linear from curved visual forms), slope as rate (reading steepness as rate of change), and curve means change (attending to how steepness itself changes across an interval). P8's reasoning maps onto two related graphical forms: *straight means constant* (linear behavior indicates stable, predictable change) and *curve means change* (a curving trajectory indicates a rate that is itself changing). The contrast between these two registrations structured P8's entire evaluation of the curves.

P8 contrasted linear behavior, associated with constant and predictable change, with accelerating behavior, where the rate itself increases, leading to more drastic shifts. They further connected steady change to the maintenance of stable conditions and incorporated *safety threshold* reasoning, rejecting red on grounds that "*I don't think it's edible*" despite its lower pH. Here, the safety threshold resource successfully tempered the "*stronger is better*" resource that might otherwise have favored red.

The cases of P2, P6, and P8 together illustrate one route to resistance reasoning: attending directly to slope or trajectory as a registration, assigning resistance meaning to it, and linking that resistance to preservation function. This direct perceptual route was not, however, the only pathway. P12, examined in the contextual conditions section, demonstrates that the same resistance reasoning can be reached through analogical reframing, and P6 demonstrates that it can be reinforced through both direct slope reading and analogical grounding simultaneously.

How activated resources link together: structural differences in preservative selection reasoning

The two activation patterns were associated with qualitatively different linking structures, each internally coherent but connected to different aspects of the preservative selection problem. Visual representations of resource activation, constructed informed by Wittmann's (2006) resource graphs and illustrating these structures for all twelve participants, are provided as supplemental material. Nine students selected yellow as the best preservative (P1, P2, P4, P5, P6, P8, P9, P10, P12), two selected red (P3, P7), and one was uncertain between red and yellow (P11). Importantly, both patterns could lead to correct answers, though through different reasoning pathways. Students activating point-based resources could arrive at yellow through elimination logic: avoid curves for which the point of interest falls in the 6–8 range, prefer lower pH for tartness, reject red for safety.

Point-based linking: comparison, elimination, and replenishment reasoning chains. Students who used point-based reasoning constructed reasoning sequences organized around discrete values and elimination logic. We interpret this pattern as reflecting activation of a *part-for-whole* resource which treats a single discrete value as representative of the system's overall character. P4's reasoning was organized around equivalence point location, identifying which curves had equivalence points outside the problematic pH 6–8 range, treating those locations as representative of each preservative's character, and eliminating options whose representative points fell within the range, arriving at yellow by elimination. This chain was internally coherent and yielded a correct answer, but it did not connect to curve shape or to how the system responds under perturbation.

P7 added a "*stronger is better*" resource layer to this pattern, treating the lowest equivalence point as representative of acid strength, and reasoning that a stronger acid would produce more tartness. P3's linking structure was the most elaborate within this group and illustrates a subtype of point-based reasoning best described as replenishment. Rather than simply eliminating options whose representative points fell in the wrong range, P3 constructed a temporal account in which tartness fades as the system becomes more basic, and a strong acid is needed to restore it. The epistemological structure remains point-based. That is, the lowest pH is still the organizing evidence, but the connecting logic is compensation for drift rather than threshold comparison. This led to selecting red. The chain was internally consistent, but preservation was framed as replenishment (adding acid to restore what is lost) rather than as resistance (maintaining pH through buffering capacity that prevents loss in the first place). Replenishment reasoning is thus not considered a third distinct pattern but a subtype of point-based reasoning, one in which the connecting inference between discrete value and selection criterion is temporal compensation.

Across all cases, reasoning was organized around a discrete value standing in for the system as a whole. The p*art-for-*whole resource is highly productive in many chemistry contexts: For instance, melting point identifies substances, equivalence point enables stoichiometric calculations, peak wavelength characterizes spectra. Its compilation through prior instruction may mean it is readily cued when students encounter any titration curve, with attention organized around discrete values in ways that are associated with slope-based resources being less likely to enter the reasoning.

Slope perception and analogy as routes to resistance reasoning. Students who activated resistance-based resources constructed linking chains that converged on resistance reasoning, which was then connected to preservation function. For most of these students, the entry point was direct slope perception; for P6 and P12, the entry point was analogical reframing. Regardless of route, the shared reasoning outcome was resistance: connecting curve behavior across an interval to a property of the system. P2's reasoning illustrates the core form of this structure: Perceiving that the slope was least steep led to the inference that pH was not changing much, which was interpreted as the system resisting change, which in turn indicated better preservation performance. Critically, this chain connected a graphical feature (slope) to a property of the system (resistance) to a functional implication (effective preservation), a causal pathway that point-based linking did not produce.

P6's linking structure was the most robust, characterized by redundancy. It featured two independent pathways: trajectory-based excluding, and rate comparison. Each independently supported yellow as the best preservative. P8's linking incorporated curve means change: Perceiving that some curves showed not just steep but accelerating slopes led to the inference that those regions indicated drastic and undesirable pH change, whereas linear regions indicated stable, manageable conditions. A third route to resistance-based linking, P12's use of a temporal metaphor as a structural bridge, is examined in the contextual conditions section which follows, where it serves as evidence of students constructively generating their own activation conditions.

The structural distinction: elimination logic *versus* explanatory reasoning. A key difference between the two linking patterns concerns whether activated resources provided an explanation for why one preservative would outperform others, or provided logic for eliminating options that violated constraints. Students with point-based reasoning generally arrived at yellow through elimination logic, or, in the cases of P3 and P7, through a "stronger is better" chain that pointed to red. Students with resistance-based reasoning, whether through direct slope perception or analogical reframing, generally arrived at yellow through a causal account connecting curve flatness to preservation function. They could explain not just that yellow was best but why its shape made it so.

Both approaches could yield correct answers in this particular task configuration. However, elimination logic is locally functional: It applies specifically to this set of curves and these constraints. Explanatory reasoning built around resistance-to-change resources may be more transferable, connecting a graphical property to a system property that recurs across contexts involving buffering or equilibrium. We conjecture that students who activated resistance resources in this task, through either slope perception or analogical reframing, may have built understanding that extends to such contexts, while students who activated elimination-based reasoning may need to reconstruct logic for each new configuration.

In the next section, we examine findings pertaining to research question 2, which addresses the contextual factors which shape resource activation.

Contextual and perceptual cues to activation

RQ2: What contextual features of the task influence which resources students activate?

Having characterized the two activation patterns and their associated linking structures, we turn to what features of the task and its graphical representations appeared to cue different activation patterns (RQ2). Three contextual dimensions emerged from the analysis: the perceptual salience of specific graphical features, the interpretive schema activated by the preservation scenario, and the cross-domain origins of resistance reasoning.

Visual salience and perceptual cueing. A consistent finding across the two activation patterns was that what students attended to in the graphs (discrete points *versus* slope) preceded and appeared to cue which resources activated. P7's explicit statement, "*I don't think the shape of it matters, necessarily... I didn't really think about it*," illustrates that curve shape was not taken up as a source of evidence within P7's reasoning framework. The same visual features that cued resistance reasoning in P2 and P6 were not registered as potential carriers of information by P4, P7, and others. For students who did attend to curve shape, flatness and small slope appear to have served as direct cues for resistance resources. P2's comment "*Because the slope is the least steep*" directly shows slope perception activating resistance reasoning. P8's distinction between "*linear*" and "*increasing at an increasing rate*" reflects more elaborate slope-based activation, where rate patterns cued different stability inferences. The visual display was identical for all students. What differed was whether and how these visual features were taken up as information-bearing.

Discussion

The following discussion builds on the evidence presented in the Results section including the case profiles, student quotes, and resource activation patterns documented there to interpret those findings in relation to prior literature and theory. The findings indicate that students differed in the types of information they extracted from the titration curves and the resources they activated in response. Rather than interpreting these differences as evidence of missing knowledge, a resources perspective frames them as patterns of differential activation and coordination (Hammer, 2000; Taber and García-Franco, 2010). The central question, therefore, is not whether students "understand buffering," but why resistance-related resources may not activate, or may not be coordinated productively, in this particular representational context.

Perceptual cueing and feature salience

One explanation involves perceptual cueing. In instructional work with titration curves, equivalence points and discrete pH values may be visually emphasized and instructionally foregrounded, strengthening activation of magnitude-based and part-for-whole resources and leading students to treat individual points as representative of entire systems. When attention centers on discrete values, slope and flatness, features that encode buffering capacity, may be less likely to be taken up as information-bearing. Talanquer (2022) argues that learners disproportionately attend to perceptually salient explicit features while overlooking implicit attributes that require interpretation, such as the rate of change encoded in curve slope. Point-based reasoning in the present study reflects exactly this pattern. The graphical forms framework (Rodriguez *et al.*, 2020a) offers a complementary vocabulary: When slope and flatness are not treated as information-bearing registrations, graphical forms such as steepness as rate and straight means constant are not recruited, even when visually present. Whether students activate these forms depends on which registrations they treat as meaningful (Rodriguez and Jones, 2024).

This interpretation aligns with work in physics education documenting slope-height confusion and domain-specific strategy activation (Ivanjek *et al.*, 2016; Planinic *et al.*, 2013). Both studies found that disciplinary framing shaped which reasoning strategies students activated, with students in physics contexts more likely to apply formula-based approaches even where slope-based reasoning was more productive, and where content knowledge rather than mathematical proficiency was the limiting factor. A similar mechanism appears to operate here: Point-based students are not graphically unsophisticated. However, the titration context appeared to cue a schema in which discrete values constitute the relevant evidence, and the content-specific knowledge linking flat regions to preservation function was not recruited.

Coordination and linking structure

A second explanatory dimension involves coordination. Sheppard and Bauer (2023) demonstrated that in buffer reasoning, productivity depends not only on which resources activate but on how resources link together and remain productive across shifting problem demands. In the present study, students who attended to discrete points activated coherent networks of comparison and elimination resources. These networks were locally functional and could yield correct answers through elimination logic, but they were not coordinated with slope-based or resistance-based resources that would connect curve shape to preservation function. By contrast, students who activated resistance resources linked slope perception to rate interpretation and preservation goals, forming more integrated reasoning structures. The key distinction lies not in resource possession but in patterns of coordination.

Epistemological framing

Epistemological framing further shapes these activation patterns. Students' assumptions about what counts as appropriate reasoning influence which conceptual resources become relevant (Hammer and Elby, 2003). If the task is implicitly framed as selecting the "strongest" preservative, then "*stronger is better*" reasoning may dominate. *Resistance* reasoning, which requires interpreting trends and system behavior under perturbation, may not be treated as evidentiary. From a Resources Perspective, this reflects not suppression of resistance resources but activation of alternative epistemological resources that redefine the problem.

Availability of resources

Importantly, the absence of slope-based reasoning does not imply the absence of resistance resources in students' repertoires. Resistance-to-change reasoning is widely available across domains: students encounter resistance in physics (forces opposing motion), in biology (homeostasis), and in everyday contexts. The present findings suggest that the preservative framing and the structure of the graph did not consistently cue those resources into activation, aligning with the cognitive resources perspective's emphasis on context sensitivity: knowledge elements may exist but remain dormant when task features cue alternative resources (diSessa, 1993; Hammer and Elby, 2003).

Contribution and synthesis

Taken together, the present study extends prior work in two ways. First, consistent with fine-grained constructivist perspectives (Hammer, 2000; Taber and García-Franco, 2010), it demonstrates that variation in reasoning is best understood as differential activation rather than conceptual deficit. Second, it provides a chemistry-specific example of how perceptual cueing and feature salience interact with coordination demands in graph interpretation (Ivanjek *et al.*, 2016; Talanquer, 2022; Sheppard and Bauer, 2023), and applies the graphical forms framework (Rodriguez *et al.*, 2020a) to show precisely how registration-schema pairings such as steepness as rate, straight means constant, and curve means change mediate between visual features and resource activation.

Rather than categorizing students as possessing or lacking understanding of buffering, this analysis highlights the mechanisms by which resource networks emerge in context. Productive resistance reasoning appears to require coordinated activation of slope interpretation, specifically, activation of a *steepness as rate* graphical form (Rodriguez *et al.*, 2020a), recognition of system behavior under perturbation, and epistemological recognition of trends as meaningful evidence. When these elements do not align, alternative but locally coherent reasoning patterns emerge. The account presented here provides the foundation for the instructional implications considered in the following section.

Instructional implications

This resource-based analysis points to instructional moves that may increase the likelihood that students activate and coordinate productive resources during titration curve interpretation. From this perspective, learning involves refining the conditions under which particular knowledge elements are activated and strengthening productive linkages among them (diSessa, 1993; Hammer, 2000; Hammer *et al.*, 2005). Instruction can support this by making relevant features more perceptually available, clarifying what counts as evidence in a given context, and helping students connect familiar forms of reasoning across domains. That is, instructors can support students by making disciplinary expectations visible rather than leaving students to infer them from task structure alone. Broader scholarship on graphing competence converges on this point, emphasizing that graph interpretation is a discipline-embedded practice that requires explicit instructional support, including helping students recognize which graphical features are relevant and how those features function as evidence within a given representational context (Gardner *et al.*, 2024).

Making slope perceptually salient

When equivalence points are visually marked but buffering regions are not, students may reasonably prioritize discrete values. Instruction may be able to counter this by explicitly drawing attention to flat regions, prompting students to compare incremental changes in pH across intervals, or asking them to quantify rate of change, increasing the likelihood that *slope-as-rate* and *resistance-to-change* resources are activated rather than remaining dormant. Empirical support for this comes from two directions. Dori and Sasson (2008) found that targeted instructional activities involving bidirectional visual and textual representations improved students' graph interpretation and chemical understanding, suggesting that how representations are structured and used in instruction shapes the interpretive strategies students bring to bear. Fernando and Perera (2022) demonstrated that dynamically visualizing pH change and buffering regions during titration supported students' conceptual understanding. From a resources standpoint, tools that foreground incremental change may help students treat slope and covariation as meaningful features rather than defaulting to discrete-value comparison.

Contrasting activation conditions

Students benefit from understanding when particular reasoning strategies are appropriate. Contrasting tasks that require equivalence-point reasoning with tasks that require slope-based interpretation can help students refine activation conditions. Comparing a concentration-determination problem with a buffering-capacity problem, for instance, may clarify that discrete values are central in one context whereas interval-based features are central in another. Such explicit contrast also supports recognition of cross-domain continuity. Many students appear to possess *resistance-to-change* reasoning from other domains, such as physics or biology, without recognizing its relevance in chemistry. Making these connections visible, by drawing parallels between familiar forms of resistance and buffering, may help students activate resources already in their repertoire rather than treating each domain's resistance phenomena as unrelated (diSessa, 1993; Hammer, 2000). Explicit discussion of both the distinctions and the continuities may together support more flexible and context-sensitive activation (Hammer *et al.*, 2005).

Supporting explanation rather than pattern recognition

Emphasizing graph shapes without linking them to underlying mechanisms may encourage pattern recognition rather than explanatory reasoning. Bowe *et al.* (2025) showed that associating shapes with concepts can activate surface-level pattern matching rather than deeper reasoning about change. Instruction that explicitly connects flat regions to incremental resistance and stability that asks things like 'what is the system doing here and why?' may help students coordinate perceptual and conceptual resources rather than relying on shape recognition alone. Students who develop this kind of explanatory connection may also be better positioned to extend resistance reasoning across chemistry topics involving stability under perturbation, such as equilibrium shifts or buffering in environmental systems, because the activation conditions are grounded in mechanism rather than surface form.

Limitations

Several limitations of this study should be noted. The sample consisted of twelve students who volunteered in response to recruitment announcements in a single second-semester general chemistry course at one institution. Volunteer samples of this size are not necessarily representative of the broader student population, and the findings should not be interpreted as reflecting the distribution of reasoning patterns across general chemistry students more generally. The goal of this qualitative study was not to establish prevalence but to characterize the nature of resource activation patterns and the contextual conditions associated with them, an analytic aim for which a small purposive sample is appropriate (Creswell and Poth, 2018).

The single-task design further limits claims about the transferability and developmental origins of the observed activation patterns. We cannot determine whether these patterns reflect stable individual tendencies or context-specific activations that might shift with different task framings, nor can we trace how they developed. The applied context used here, juice preservation with dual constraints of tartness maintenance and microbial inhibition, foregrounds pH stability across a range in ways that may not generalize to other framings or student populations.

Future research could address these limitations through complementary approaches. For instance, transfer tasks using varied graph types could test whether activation patterns persist across contexts. Instructional comparison studies could examine whether targeted interventions, such as emphasizing slope or drawing cross-domain analogies, increase activation of rate- and resistance-based resources. Studies conducted across different institutional contexts and student populations would clarify the generalizability of these findings. Studies that follow students across course levels, for instance from general chemistry into Quantitative Analysis, could provide longitudinal insight into how resource activation patterns develop and stabilize across the curriculum. Such extensions would also test the predictive value of resource-based analyses for learning trajectories and instructional design, and clarify whether supporting productive activation leads to more transferable understanding.

Conclusions

This study contributes an account of variation in titration curve interpretation grounded in differential resource activation rather than differential knowledge. The two patterns identified (point-based reasoning and resistance-based reasoning) were not simply differences in correctness but differences in what information students extracted from the curves, how they entered their reasoning, and how they linked that information to preservation function. That both patterns could yield correct answers underscores the importance of examining reasoning structure, not just answer accuracy. The finding that several point-based students noticed slope before redirecting attention to equivalence points suggests that relevant resources were available but not taken up as evidentiary, a distinction that deficit-based accounts cannot easily capture. Tasks designed around stoichiometric endpoints will not reveal whether students possess resistance resources; tasks that foreground system behavior create conditions under which that variation becomes visible. Designing instruction and assessment to make slope and resistance salient alongside discrete values may be a more tractable lever for supporting flexible reasoning than expanding content coverage alone.

Author contributions

A. Farheen: formal analysis; validation; conceptualization; methodology; investigation; data curation; writing – review & editing; A. Salmon: formal analysis; methodology; M. Mishulin: formal analysis. N. M. Becker: supervision; funding acquisition; project administration; writing – original draft; resources.

Conflicts of interest

The authors declare that they have no competing financial, personal, or professional interests that could inappropriately influence (or be perceived to influence) the work described in this manuscript. All support for the research—including funding, materials, and institutional resources—has been fully disclosed.

Data availability

The data that support the findings of study were collected from human subjects and are not publicly available due to confidentiality and ethical restrictions.

Supplementary information (SI): Appendix A: Code definitions and exemplars; Appendix B: Visual representations of resource activation. See DOI: https://doi.org/10.1039/d5rp00456j.

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