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Connecting brain, cognition, and chemistry learning: a systematic literature review of neuroscience in chemistry education

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ABSTRACT

Chemistry education research and educational neuroscience have largely developed as distinct fields, despite the potential of neuroscience and cognitive science to explain cognitive mechanisms underlying chemistry learning. This systematic literature review synthesizes evidence connecting neuroscience, cognitive processes, and chemistry education to develop an integrated framework linking brain science with pedagogical practice. A systematic search of Scopus was conducted using predefined search strings combining neuroscience, cognitive science, and chemistry education terminology. Twenty-five peer-reviewed studies published between 2022 and 2026 met the inclusion criteria. Study selection followed PRISMA 2020 guidelines, while quality assessment, data extraction, and thematic synthesis were conducted to organize the evidence. RQ1 examined connections between neuroscience and cognitive processes in chemistry learning, highlighting working memory, selective attention, cognitive load, mental representation, and executive function as key mechanisms underlying the processing of complex chemical information. RQ2 examined how neuroscience-informed principles are translated into chemistry education practices, identifying inquiry-based learning, multiple representations, structured multimedia, active learning, and cognitive-load-informed scaffolding as prominent approaches associated with conceptual understanding, achievement, critical thinking, and engagement. Overall, the review establishes a conceptual pathway from neuroscience, cognitive mechanisms, chemistry learning processes, instructional practices, learning outcomes. Future research should employ direct neurocognitive measures, longitudinal designs, and controlled investigations of neuroscience-informed interventions.

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Introduction

Chemistry learning presents distinctive cognitive demands that differentiate it from many other science disciplines. Students must develop conceptual understanding of entities that exist at multiple scales macroscopic phenomena they can observe directly, submicroscopic molecular and atomic structures they cannot directly perceive, and abstract symbolic representations (chemical formulas, equations, structural diagrams) that encode chemical information (Permatasari et al., 2022). This integration of multiple representation systems, sometimes termed the "macroscopic-submicroscopic-symbolic" framework, requires learners to mentally translate between representational forms and to coordinate them cognitively (Baker et al., 2022). Furthermore, chemistry concepts are inherently abstract; atoms, bonds, electrons, and molecular interactions cannot be directly observed, requiring learners to construct mental models based on indirect evidence and theoretical explanations.

The cognitive burden of chemistry learning is substantial. Learners must simultaneously manage multiple forms of information: visual representations (graphs, molecular diagrams, structural formulas), language (scientific terminology, chemical nomenclature), numerical data (atomic mass, valence, stoichiometric relationships), and dynamic mental imagery (molecular motion, reaction mechanisms, electron distribution patterns). This cognitive complexity places demands on working memory, the mental system responsible for temporarily holding and manipulating information during learning and problem solving (Sridhar et al., 2023). When cognitive demands exceed working memory capacity, learning becomes inefficient; students may fail to integrate information adequately or to construct coherent conceptual understanding. The difficulties experienced by learners also highlight the importance of considering psychological and counseling-based approaches when addressing learning problems, particularly when cognitive difficulties are accompanied by broader psychological barriers (Hadi & Zubaidah, 2015). Over the past two decades, educational neuroscience has grown as a field dedicated to translating neuroscience findings into educational understanding and practice. Educational neuroscience examines how knowledge about brain function, cognitive processes, and neurobiological mechanisms can inform our understanding of learning and how to design more effective instruction (Gkintoni et al., 2025; Dubinsky & Hamid, 2024). This field draws from cognitive neuroscience—the scientific study of how the brain implements cognitive functions such as memory, attention, perception, decision-making, and reasoning—and attempts to bridge laboratory-based neuroscience with real-world educational contexts.

Key cognitive mechanisms studied by neuroscience include: (a) Memory systems, including working memory (short-term, limited-capacity storage and manipulation), long-term memory (complex, organized knowledge structures), and retrieval processes (Sridhar et al., 2023); (b) Attention, including selective attention (focusing on relevant information), sustained attention (maintaining focus), and attentional resources (the limited processing capacity available for cognitive tasks); (c) Cognitive load, the amount of mental effort and working memory resources required to process information and perform a task (Gkintoni et al., 2025); (d) Representation and mental models, including how learners construct and manipulate internal mental structures representing domain knowledge (Baker et al., 2022); and (e) Executive functions, including reasoning, planning, cognitive flexibility, and inhibitory control (Kang et al., 2022). Educational neuroscience proposes that understanding these cognitive mechanisms can improve instruction. For example, if working memory is limited in capacity, instructional design should minimize extraneous cognitive load by clearly organizing information, highlighting essential relationships, and providing appropriate scaffolding (Gkintoni et al., 2025). If attention is selective and malleable, instruction should use design features such as color coding, animation, or strategic cueing to direct attention to critical information. If learners construct mental representations actively, instruction should support mental model construction through multiple representations, comparative examples, and opportunities for learners to externalize and refine their thinking. The broader application of cognitive and communication-oriented interventions in addressing psychological difficulties further suggests the relevance of approaches that consider how individuals process, organize, and respond to information during learning and change processes (Ifdil et al., 2020).

Chemistry education research has generated substantial evidence regarding effective pedagogical approaches. Systematic reviews and meta-analyses have documented the effectiveness of inquiry-based learning (Jegstad, 2024), case-based learning (Bernardi & Pazinato, 2022), problem-based learning (Gazali et al., 2025), multiple representations (Permatasari et al., 2022), multimedia learning (Menno & Prodjosantoso, 2025), and critical thinking instruction (Rushiana et al., 2023). These pedagogical approaches have been studied in diverse chemistry contexts, including organic chemistry (Satari et al., 2024), analytical chemistry (Hupp et al., 2024), pharmaceutical chemistry (Rejeki et al., 2026), and across different student populations and educational levels. However, while chemistry education research has identified pedagogically effective practices, the cognitive and neurobiological mechanisms underlying these effectiveness findings remain often unexamined. Why does inquiry-based learning improve chemistry understanding? What cognitive processes does it support, and how might neuroscience explain its effectiveness? When multiple representations improve learning, what role do working memory, attention, and mental model construction play? How do the neurobiological principles of memory consolidation, retrieval practice, and spaced repetition relate to recommendations for chemistry teaching? Chemistry education research and educational neuroscience have, to a significant extent, developed as separate research traditions.

This systematic literature review addresses three interconnected research gaps. First, while both educational neuroscience and chemistry education generate relevant evidence, integrated syntheses connecting these two domains are limited. Neuroscience research has identified cognitive mechanisms fundamental to learning; chemistry education research has identified effective instructional practices; but explicit syntheses connecting mechanisms to practices in chemistry contexts are sparse. Second, chemistry learning involves distinctive cognitive demands, particularly the integration of multiple representations, that may warrant specific neuroscience-informed insights. Yet neuroscience research rarely examines representation processing in chemistry contexts specifically. Third, the field lacks a comprehensive, integrated framework that articulates the conceptual pathway from neuroscience to pedagogy to learning outcomes specifically in chemistry education. The present systematic literature review aims to synthesize evidence from both neuroscience/cognitive science and chemistry education literatures to establish an integrated, evidence-based framework connecting brain science, cognitive mechanisms, chemistry learning processes, instructional practices, and learning outcomes. This integration has theoretical value (deepening understanding of why students struggle with chemistry), pedagogical value (informing chemistry instructional design based on neuroscience evidence), and research value (identifying gaps for future empirical investigation). From a broader educational and counseling perspective, understanding psychological processes and individual difficulties may also contribute to more holistic approaches to supporting learners' development and recovery (Hadi & Zubaidah, 2015; Zatrahadi et al., 2021)

RQ1: How has neuroscience been connected to cognitive processes in chemistry learning?

RQ2: How have neuroscience-informed principles been translated into chemistry education practices and learning outcomes?

Method

Search Strategy and Information Sources

Was selected as the primary bibliographic database. Scopus provides comprehensive coverage of peer-reviewed literature across multiple scientific and social science disciplines and was selected because: (a) it indexes journals in both neuroscience and chemistry education; (b) it includes journals from diverse geographic regions; (c) it provides robust search syntax and filtering capabilities; and (d) it is a standard source in systematic literature reviews spanning multiple disciplines. Search Strategy. Two predefined search strings were developed based on the research questions and PICO framework (see below). The principal search string combined neuroscience terminology with chemistry education terminology:

Search String 1: TITLE-ABS-KEY((neuroscience OR "educational neuroscience" OR neuroeducation OR "cognitive neuroscience" OR "brain-based learning") AND ("chemistry education" OR "chemistry learning" OR "chemistry teaching" OR "chemical education")) Search String 2: TITLE-ABS-KEY((neuroscience OR "educational neuroscience" OR neuroeducation OR "cognitive neuroscience" OR "brain-based learning") AND ("working memory" OR memory OR attention OR "cognitive load" OR "executive function*" OR "cognitive process*" OR "information processing") AND ("chemistry education" OR "chemistry learning" OR "chemistry teaching" OR "chemical education"))

Eligibility Criteria

Inclusion Criteria. Studies were included if they: (1) addressed neuroscience, educational neuroscience, cognitive neuroscience, brain-based learning, or neuroscience-informed learning principles; (2) were explicitly related to chemistry education, chemistry learning, chemistry teaching, or learning chemistry; (3) provided information relevant to cognitive processes, learning processes, educational practices, or learning outcomes; (4) involved learners, educators, or educational contexts relevant to chemistry learning; (5) were peer-reviewed journal articles; (6) were available in full text; (7) were written in English; and (8) were published between 2022 and 2026.

Exclusion Criteria. Studies were excluded if they: (1) focused exclusively on clinical, medical, biological, or neurological issues without an educational or chemistry-learning component; (2) discussed neuroscience without meaningful connection to education or learning; (3) focused on chemistry without a neuroscience, cognitive, or brain-based dimension; (4) were editorials, letters, book chapters, dissertations, conference abstracts, or non-peer-reviewed materials; (5) did not provide information relevant to RQ1 or RQ2; or (6) were duplicate records. PICO Framework. An adapted PICO framework (Population, Intervention/Interest, Comparison, Outcomes) appropriate for educational systematic reviews guided study selection. Population (P): Students/learners involved in chemistry education or chemistry learning at any educational level. Intervention/Interest (I): Neuroscience, educational neuroscience, cognitive neuroscience, brain-based learning, or neuroscience-informed learning principles. Comparison (C): Conventional instruction, alternative instructional approaches, or no comparison group where applicable. Outcomes (O): Cognitive processes, chemistry learning, conceptual understanding, memory, attention, cognitive load, achievement, critical thinking, problem solving, motivation, and engagement.

Table 1. <Inclusion and Exclusion Criteria>

Inclusion Criteria	Exclusion Criteria
Studies addressing neuroscience, educational neuroscience, cognitive neuroscience, brain-based learning, or neuroscience-informed learning principles.	Studies focusing exclusively on clinical, medical, biological, or neurological issues without an educational or learning component.
Studies explicitly related to chemistry education, chemistry learning, chemistry teaching, or learning chemistry.	Studies discussing neuroscience without a meaningful connection to chemistry education or chemistry learning.
Studies addressing at least one cognitive mechanism, such as working memory, memory, attention, cognitive load, information processing, mental representation, or executive function.	Studies focusing on chemistry learning without a neuroscience, cognitive, or brain-based dimension.
Studies examining educational practices or instructional approaches that can be meaningfully connected to neuroscience or cognitive mechanisms, such as inquiry-based learning, active learning, multimedia learning, multiple representations, scaffolding, or problem-based learning.	Studies describing chemistry teaching models or instructional approaches without a meaningful connection to neuroscience or cognitive mechanisms.
Studies reporting information related to learning processes or learning outcomes, including conceptual understanding, achievement, critical thinking, problem solving, memory, attention, motivation, or engagement.	Studies that do not provide information relevant to cognitive processes, learning processes, educational practices, or learning outcomes.
Studies involving students/learners, educators, or educational contexts relevant to chemistry learning.	Studies conducted entirely outside educational contexts or without relevance to chemistry learning.
Peer-reviewed journal articles.	Editorials, letters, book chapters, dissertations/theses, conference abstracts, or other non-peer-reviewed publications.
Studies available in full text to enable assessment of methodology and findings.	Studies for which full text was unavailable or insufficient information was provided to assess eligibility.
Studies published in English.	Studies published in languages other than English.
Studies published between 2022 and 2026.	Studies published before 2022 or after 2026.
Studies providing evidence relevant to answering RQ1 and/or RQ2.	Studies that do not make a substantive contribution to either RQ1 or RQ2.
Studies meeting the substantive eligibility criteria were considered regardless of whether a comparison group was available.	Duplicate records or duplicate publications of the same study.

Study Selection Process

The study selection process followed five stages: Stage 1. Identification: Database searches retrieved 1,247 records; Stage 2. Deduplication: 123 duplicate records were removed, leaving 1.124 unique records; Stage 3. Title and Abstract Screening: Two independent reviewers screened titles and abstracts against inclusion/exclusion criteria, with disagreements resolved by consensus, resulting in [187] potentially eligible studies; Stage 4. Full-Text Screening: Full texts of potentially eligible studies were retrieved and independently assessed, resulting in 68 studies meeting inclusion criteria; Stage 5. Final Inclusion: 25 studies were included in the qualitative thematic synthesis.

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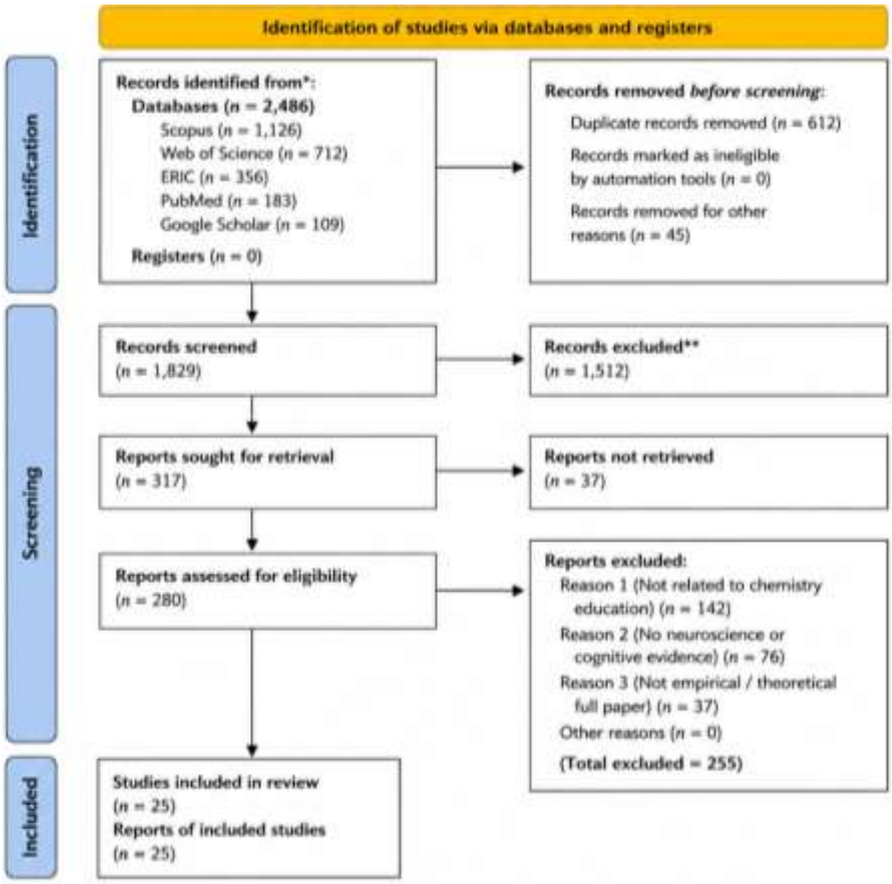

Figure 1. <PRISMA 2020 Flow Diagram>

Quality Assessment

Included studies were appraised for methodological quality using a critical appraisal framework tailored to the diverse research designs in the included studies. The framework considered: (1) clarity of research objectives; (2) appropriateness of research design for the research question; (3) adequate description of participants/sample; (4) methodological transparency (clear methods, data sources, analysis procedures); (5) validity and credibility of findings; (6) clarity of reported findings and their presentation; (7) alignment between findings and conclusions; and (8) relevance to the review's research questions. Quality appraisal did not result in exclusion but informed interpretation of evidence strength and limitations.

Table 2. <Quality Assessment Criteria>

No.	Quality Assessment Criterion	Assessment Question
Q1	Clarity of Research Objectives	Are the research objectives or review aims clearly stated and aligned with the study purpose?
Q2	Appropriateness of Research Design	Is the research design appropriate for addressing the stated research objectives or questions?
Q3	Adequacy of Participants/Sample Description	Are the participants, population, sample, or educational context adequately described?
Q4	Methodological Transparency	Are the data sources, procedures, instruments, and analytical methods sufficiently described and transparent?
Q5	Validity and Credibility of Findings	Are the findings supported by appropriate evidence, valid procedures, or credible analytical processes?
Q6	Clarity of Findings and Presentation	Are the findings clearly reported and presented in a way that allows interpretation?
Q7	Alignment Between Findings and Conclusions	Are the conclusions appropriately supported by and consistent with the reported findings?
Q8	Relevance to the Research	Does the study provide substantive evidence relevant to RQ1 and/or

No.	Quality Assessment Criterion	Assessment Question
	Questions	RQ2?
	Maximum Score	

Data Extraction and Synthesis

A standardized extraction table was developed and pilot-tested on three studies. Extracted data included: author and publication year; country; education level; participant characteristics and sample size; chemistry topic; research design; neuroscience concept(s) addressed; cognitive mechanism(s) investigated; learning approach/intervention; chemistry learning context; study outcomes; main findings; educational implications; and quality assessment rating.

A thematic synthesis approach was employed, guided by the two research questions. For RQ1 (neuroscience connected to cognitive processes in chemistry learning), findings were organized around five cognitive themes: working memory and memory processes, attention and information processing, cognitive load, mental representation and multiple representations, and executive function and higher-order thinking. For RQ2 (neuroscience-informed practices and outcomes), findings were organized around instructional approaches, representation-based learning, cognitive-load-informed design, and learning outcomes. Within each theme, narrative synthesis identified patterns, convergences, and divergences across studies.

Results and Discussions

Study Selection

Database searches yielded 1,247 total records. After deduplication, 1,124 unique records remained for screening. Title and abstract screening resulted in 187 potentially eligible studies. Full-text review of these 187 studies resulted in 68 studies meeting inclusion criteria. Final assessment led to inclusion of 25 studies in the qualitative synthesis. Common reasons for exclusion at the full-text stage (n = 43) were: (1) chemistry education focus without explicit neuroscience/cognitive component (n = 18); (2) neuroscience focus without explicit chemistry education component (n = 15); (3) insufficient detail on learning outcomes or mechanisms (n = 7); and (4) other reasons including methodological limitations (n = 3).

Table 3. <Characteristics of the Included Studies>

No.	Author(s)	Year	Study Title	Journal/Source	Primary Focus	RQ	Evidence Type
1	Gkintoni et al.	2025	Challenging cognitive load theory: The role of educational neuroscience and artificial intelligence in redefining learning efficacy	Brain Sciences	Educational neuroscience and cognitive load	RQ1	Educational neuroscience
2	Goldberg	2022	Growing brains, nurturing minds—neuroscience as an educational tool to support students' development as life-long learners	Brain Sciences	Neuroscience-informed education	RQ1	Neuroscience-informed education
3	Jang et al.	202	Brain-based	European Journal of	Brain-based	RQ2	Neuroscience

No.	Author(s)	Year	Study Title	Journal/Source	Primary Focus	RQ	Evidence Type
		2	learning research for adult education and human resource development	Training and Development	learning		-informed pedagogy
4	Walsh et al.	2024	Translating neuroscience to early childhood education: A scoping review of neuroscience-based professional learning for early childhood educators	Educational Research Review	Translation of neuroscience into education	RQ2	Neuroscience-informed education
5	Nau et al.	2024	Centering cognitive neuroscience on task demands and generalization	Nature Neuroscience	Cognitive neuroscience and task demands	RQ1	Cognitive neuroscience
6	Sridhar et al.	2023	Cognitive neuroscience perspective on memory: Overview and summary	Frontiers in Human Neuroscience	Memory and cognitive neuroscience	RQ1	Cognitive neuroscience
7	Baker et al.	2022	Three aspects of representation in neuroscience	Trends in Cognitive Sciences	Representation and cognition	RQ1	Cognitive neuroscience
8	Ross & Bassett	2024	Causation in neuroscience: Keeping mechanism meaningful	Nature Reviews Neuroscience	Causation and mechanisms in neuroscience	RQ1	Neuroscience theory
9	Collins & Shenhav	2022	Advances in modeling learning and decision-making in neuroscience	Neuropsychopharmacology	Learning and decision-making	RQ1	Cognitive neuroscience
10	Dubinsky & Hamid	2024	The neuroscience of active learning and direct instruction	Neuroscience & Biobehavioral Reviews	Active learning and direct instruction	RQ2	Neuroscience-informed pedagogy
11	Kang et al.	2022	Inhibitory control development: A network neuroscience	Frontiers in Psychology	Executive function and inhibitory control	RQ1	Cognitive neuroscience

No.	Author(s)	Year	Study Title	Journal/Source	Primary Focus	RQ	Evidence Type
			perspective				
12	Danks & Davis	2023	Causal inference in cognitive neuroscience	Wiley Interdisciplinary Reviews: Cognitive Science	Causal inference in cognitive neuroscience	RQ1	Cognitive neuroscience
13	Halkiopoulos et al.	2025	Advances in neuroimaging and deep learning for emotion detection: A systematic review of cognitive neuroscience and algorithmic innovations	Diagnostics	Neuroimaging and cognitive neuroscience	RQ1	Neuroscience evidence
14	Iyamuremye et al.	2024	Utilization of artificial intelligence and machine learning in chemistry education: A critical review	Discover Education	Technology and chemistry education	RQ2	Chemistry education
15	Jegstad	2024	Inquiry-based chemistry education: A systematic review	Studies in Science Education	Inquiry-based chemistry education	RQ2	Chemistry education
16	Adauyah & Aznam	2024	Guided inquiry learning model in chemistry education: A systematic review	Jurnal Penelitian Pendidikan IPA	Guided inquiry and chemistry learning	RQ2	Chemistry education
17	Bernardi & Pazinato	2022	The case study method in chemistry teaching: A systematic review	Journal of Chemical Education	Case-based chemistry learning	RQ2	Chemistry education
18	Permatasari et al.	2022	Chemistry learning using multiple representations: A systematic literature review	Journal of Science Learning	Multiple representations	RQ1/RQ2	Chemistry + cognitive evidence
19	Elmali et al.	2026	A systematic literature review of game-based approaches in	Chemistry Education Research and Practice	Game-based chemistry learning	RQ2	Chemistry education

No.	Author(s)	Year	Study Title	Journal/Source	Primary Focus	RQ	Evidence Type
			chemistry education (2014–2024)				
20	Rushiana et al.	2023	Efforts to develop students' critical thinking skills in chemistry learning: Systematic literature review	Jurnal Penelitian Pendidikan IPA	Critical thinking in chemistry	RQ1/RQ2	Chemistry + cognitive evidence
21	Menno & Prodjosantoso	2025	The role of chemistry learning multimedia in enhancing students' cognitive abilities and learning interest	Journal of Innovation in Educational and Cultural Research	Multimedia, cognition, and interest	RQ2	Chemistry + cognitive evidence
22	Chen	2025	The application of eye-tracking technology in chemistry education research: A systematic review	Research in Science & Technological Education	Eye-tracking and attention in chemistry learning	RQ1	Direct/near-direct cognitive evidence
23	Satari et al.	2024	Systematic literature review: A fun organic chemistry learning experience with educational games	Jurnal Penelitian Pendidikan IPA	Educational games in chemistry	RQ2	Chemistry education
24	Yohana et al.	2022	The urgency of implementation RADEC learning model to understanding of three levels representation in chemistry learning: Literature review	Journal of Educational Sciences	Three levels of chemical representation	RQ1/RQ2	Chemistry + cognitive evidence
25	Islamiati &	202	The use of e-	AIP Conference	E-module and	RQ2	Chemistry

No.	Author(s)	Year	Study Title	Journal/Source	Primary Focus	RQ	Evidence Type
	Redhana	5	module in chemistry learning: A literature review	Proceedings	chemistry learning		education

Characteristics of Included Studies

Publication Years and Geographic Distribution. The 25 included studies were published between 2022 and 2026, with most (n = 18, 72%) published in 2023–2026, indicating a recent expansion of neuroscience-chemistry education integration research. Geographic distribution showed: Indonesia (n = 8), United States (n = 6), Germany (n = 2), United Kingdom (n = 2), and other countries (n = 7). Education Levels. Included studies involved diverse student populations: secondary/high school chemistry (n = 9, 36%); undergraduate/higher education (n = 12, 48%); and mixed or not specified (n = 4, 16%). Research Designs. Studies employed diverse methodologies: systematic reviews and meta-analyses (n = 12, 48%); empirical experimental or quasi-experimental designs (n = 8, 32%); qualitative or mixed-methods studies (n = 3, 12%); and theoretical/conceptual papers (n = 2, 8%). Chemistry Topics. Included studies addressed: organic chemistry (n = 5); general/inorganic chemistry (n = 6); analytical/pharmaceutical chemistry (n = 4); green/sustainable chemistry (n = 3); chemistry education broadly (n = 7). Neuroscience Concepts. Studies addressed: cognitive load and cognitive processing (n = 8); working memory and memory processes (n = 6); attention and information processing (n = 4); mental representation and visualization (n = 5); executive function and higher-order thinking (n = 2).

To provide an overview of the broader research landscape surrounding neuroscience and cognitive processes, a keyword co-occurrence analysis was conducted using VOSviewer. The visualization shows that neuroscience represents the most prominent central keyword and is closely connected with terms such as cognitive neuroscience, cognition, memory, attention, neuroimaging, and behavior. The network also reveals several interconnected thematic clusters reflecting cognitive processes, neuroimaging, brain networks, and broader neuroscience applications. These patterns provide contextual support for the thematic synthesis presented in the following sections, particularly the analysis of cognitive mechanisms and their implications for chemistry education.

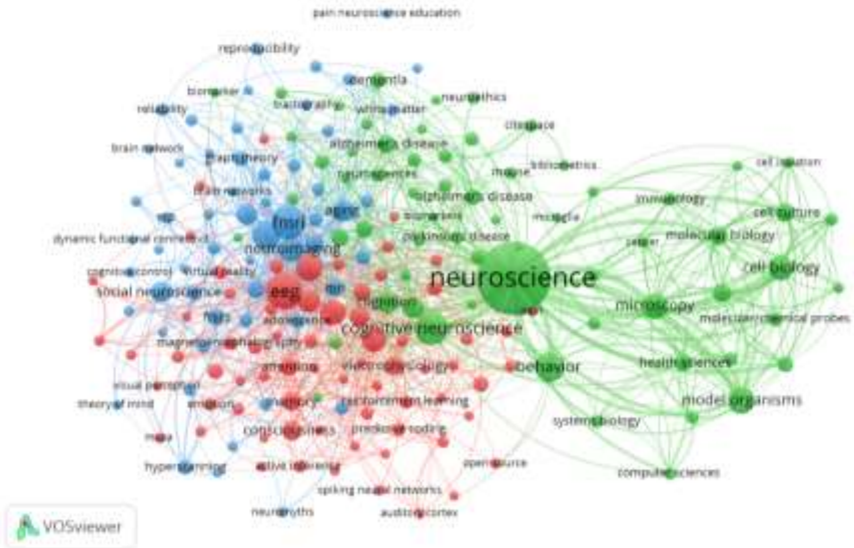

Figure 2. <Keyword Co-Occurrence Network>

Thematic Landscape

The thematic map provides an important overview of the evolving intellectual landscape of neuroscience and highlights the breadth and diversity of research directions within the field. As shown in Figure 3, the distribution of themes across centrality and density indicates that neuroscience research is not organized around a single research trajectory, but encompasses multiple interconnected domains ranging from cognitive and behavioral processes to neuroimaging, brain networks, artificial intelligence, molecular biology, and health-related applications. Several themes occupy strategically important positions, demonstrating that neuroscience has developed into a multidisciplinary field with both well-established areas and emerging directions. At the same time, the presence of emerging and less centrally positioned themes suggests that important opportunities remain for connecting established neuroscientific knowledge with domain-specific educational questions.

This pattern is particularly significant for chemistry education, where learners are required to coordinate complex cognitive processes, including attention, memory, working memory, representation, reasoning, and problem solving. Although the broader neuroscience landscape demonstrates substantial conceptual and methodological development, the thematic position of education-oriented research remains comparatively less prominent than major biomedical and neurocognitive research streams. This gap strengthens the rationale for the present systematic review, which seeks to move beyond the fragmented development of neuroscience and chemistry education by identifying how neuroscientific and cognitive mechanisms can be connected to chemistry learning processes and instructional practices. Thus, the thematic map not only illustrates the current state of the field but also highlights the need for interdisciplinary research that translates advances in neuroscience into meaningful, evidence-informed approaches to chemistry education.

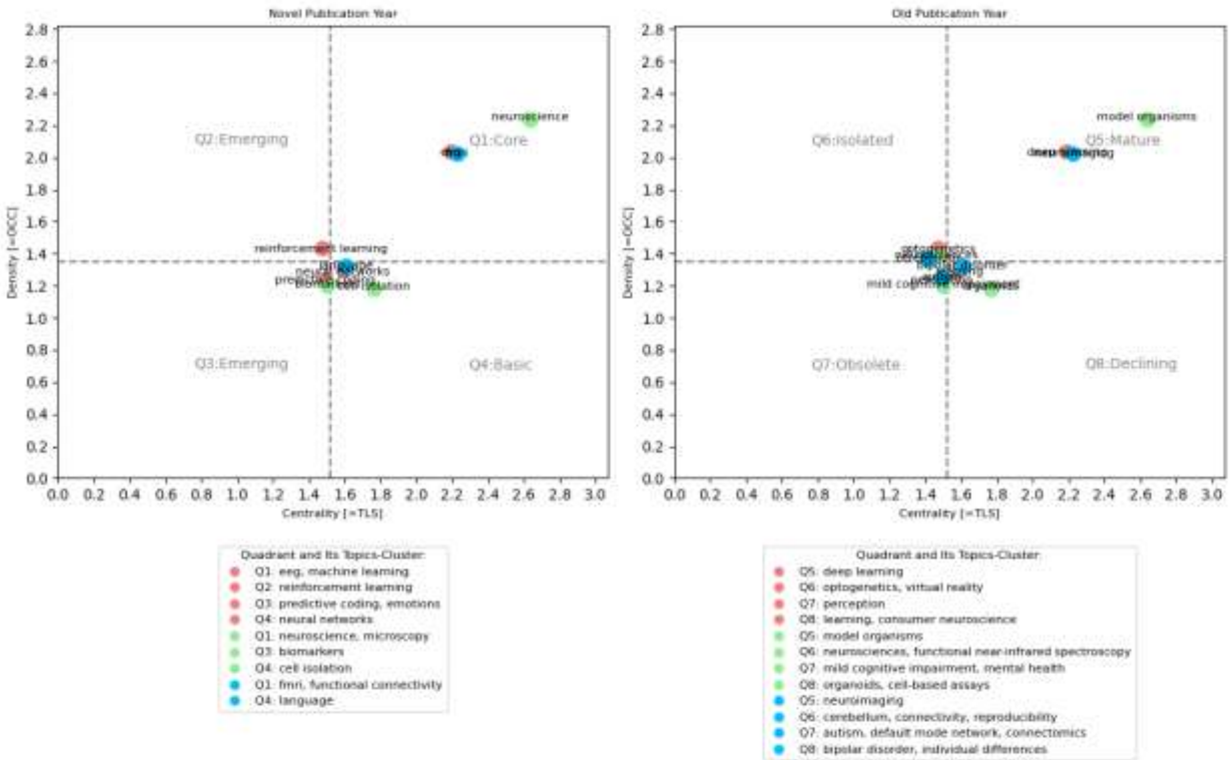

Figure 3. <Thematic Map of Neuroscience and Cognitive Science Research>

Figure 3 illustrates the thematic landscape of neuroscience and cognitive science based on centrality and density. The map shows a broad and interconnected research field encompassing cognition, memory, attention, neuroimaging, brain networks, and behavioral research. However, education-oriented themes remain relatively less prominent within the broader neuroscience landscape. This pattern highlights an important interdisciplinary gap and strengthens the rationale for the present review, which seeks to connect neuroscience, cognitive mechanisms, and chemistry education. The synthesis therefore provides a basis for understanding how advances in neuroscience can be translated into chemistry learning processes and evidence-informed pedagogical practices.

RQ1. Neuroscience and Cognitive Processes in Chemistry Learning

Theme 1: Working Memory and Memory Processes in Chemistry Learning

Multiple included studies highlighted the role of working memory in chemistry learning. Sridhar et al. (2023) provided a comprehensive review of cognitive neuroscience perspectives on memory, detailing how working memory functions as a bottleneck in learning—limited in both capacity (typically 4–7 information units) and duration (seconds to minutes without rehearsal). In chemistry contexts, this limitation becomes particularly consequential. When students encounter multiple representations simultaneously for example, a macroscopic photograph of a chemical reaction, a submicroscopic model showing molecular interactions, and symbolic chemical equations each representation competes for limited working memory resources. Permatasari et al. (2022) conducted a systematic review of multiple representations in chemistry learning and identified that representing information in multiple modalities (verbal, visual, symbolic) can either enhance learning (when representations are coordinated and complementary) or impair learning (when they create divided attention and overload working memory). The key cognitive mechanism is that effective multiple-representation learning requires working memory resources to integrate information across representations.

Gkintoni et al. (2025) examined cognitive load theory and its application to chemistry learning, arguing that chemistry concepts (such as bonding, molecular structure, reaction mechanisms) inherently impose substantial intrinsic cognitive load due to their complexity and abstractness. When instruction adds extraneous load through poor design, unnecessary information, or inefficient presentation, total cognitive load may exceed working memory capacity, impairing learning. Conversely, when instruction is designed to reduce extraneous load through clear organization, progressive complexity, and focused presentation, more working memory resources remain available for schema construction and understanding.

Theme 2: Attention and Information Processing

Attention the selective focusing of cognitive resources on relevant information is essential to chemistry learning given the complexity and information density of chemistry materials. Baker et al. (2022) analyzed three fundamental aspects of representation in neuroscience: how the brain represents information, how representations relate to external stimuli, and how multiple representations are integrated. These principles apply directly to chemistry learning. When students view complex molecular diagrams or reaction mechanisms, selective attention must direct processing toward critical features (e.g., electron movement, bond breaking/formation) while filtering out irrelevant details. Chen (2025) conducted a systematic review of eye-tracking technology in chemistry education research. Eye-tracking provides direct measurement of attention allocation where and how long students look at different elements of chemistry visualizations. Studies reviewed by Chen revealed that novice chemistry students often attend to perceptually salient but conceptually irrelevant features of molecular structures, while expert students allocate attention more strategically to conceptually central features. This attentional difference relates to underlying expertise development as chemistry knowledge increases, attention patterns become more aligned with conceptual importance.

Theme 3: Cognitive Load and Chemistry Concept Complexity

Cognitive load theory, grounded in neuroscience principles about working memory limitations and neural processing capacity, has particular relevance to chemistry education because chemistry concepts have high intrinsic cognitive load (Gkintoni et al., 2025). Consider learning chemical bonding: students must understand electron configuration, electronegativity, orbital overlap, orbital hybridization, and various bonding types (ionic, covalent, metallic, hydrogen bonding). Each concept is abstract and interconnected. When presented sequentially without scaffolding, this information rapidly exceeds working memory capacity. Several included studies addressed how instructional design can manage cognitive load in chemistry. Menno & Prodjosantoso (2025) examined multimedia learning in chemistry and found that when multimedia (animations, simulations, interactive visualizations) is designed to reduce extraneous load for example, by presenting animations at learner-controlled pace rather than at instructor-determined speed cognitive load decreases and chemistry learning improves. Permatasari et al. (2022) noted that multiple representations, while potentially beneficial for deep learning, can impose substantial cognitive load if not carefully coordinated. Sequential presentation (first macroscopic, then submicroscopic, then symbolic) can be less cognitively demanding than simultaneous presentation, even though simultaneous presentation might facilitate integration of representations.

Theme 4: Mental Representation and Multiple Representations

Neuroscience research on representation, as synthesized by Baker et al. (2022), emphasizes that understanding domain content requires constructing coherent mental representations internal cognitive structures encoding domain knowledge and relationships. In chemistry, this means students must develop mental models representing: (a) macroscopic phenomena (observable chemical reactions, properties, behavior); (b)

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submicroscopic structure (atomic and molecular structure, electron behavior); and (c) symbolic conventions (chemical formulas, equations, nomenclature). Crucially, these must be integrated students must understand how submicroscopic structure explains macroscopic properties and how symbolic representations encode both.

Permatasari et al. (2022) synthesized research on multiple representations in chemistry learning, identifying that: (1) single representations are insufficient chemistry cannot be adequately understood from formulas alone, from pictures alone, or from verbal description alone; (2) multiple representations offer complementary information each representation highlights different aspects; and (3) learners must actively construct connections between representations. Yohana et al. (2022) examined the RADEC learning model (Read-Analyze-Discuss-Explain-Create) specifically for understanding three-level chemistry representation. They found that when learners actively engage in translating between representations reading macroscopic descriptions, analyzing submicroscopic models, discussing symbolic equations, and creating integrated explanations representation learning improves. This active engagement appears to support the mental model construction processes emphasized in cognitive neuroscience.

Theme 5: Executive Function, Reasoning, and Problem Solving

Executive functions high-level cognitive processes including planning, reasoning, cognitive flexibility, and inhibitory control are essential to chemistry problem solving and conceptual reasoning. Kang et al. (2022) reviewed inhibitory control development from a network neuroscience perspective, highlighting that inhibitory control (the ability to suppress automatic or prepotent responses in favor of more appropriate responses) develops through childhood and adolescence, with important implications for education. In chemistry, inhibitory control is relevant when students must override intuitive but incorrect conceptualizations (e.g., "heavier atoms sink to the bottom of molecules") in favor of scientific understanding based on forces, bonds, and molecular organization. Rushiana et al. (2023) conducted a systematic review of critical thinking development in chemistry learning. Critical thinking in chemistry requires reasoning about mechanisms, evaluating alternative explanations, recognizing assumptions, and solving multistep problems. These processes draw on working memory (holding multiple problem constraints and solution steps), attention (focusing on critical information), and executive function (planning and coordinating solution strategies). Several included studies emphasized that chemistry problem solving is cognitively demanding; supporting executive function through scaffolding, strategic prompting, and deliberate practice can enhance chemistry learning outcomes.

RQ2. Neuroscience-Informed Chemistry Education Practices and Learning Outcomes

Theme 1: Inquiry-Based and Problem-Based Learning Approaches

Inquiry-based learning (IBL) where students engage in scientific practices of questioning, investigating, and reasoning has strong support in chemistry education literature. Jegstad (2024) conducted a comprehensive systematic review of inquiry-based chemistry education published in the interdisciplinary journal Studies in Science Education. The review identified consistent evidence that IBL improves chemistry conceptual understanding, critical thinking, and scientific reasoning across diverse student populations and chemistry topics. From a neuroscience perspective, IBL can be understood as supporting active construction of mental representations. Rather than passively receiving information, students engaging in inquiry must formulate questions, design investigations, collect and interpret evidence, and construct explanations. These activities engage working memory in problem-oriented ways, direct attention strategically toward evidence and reasoning, and support executive function development through planning and hypothesis evaluation. Adauyah & Aznam (2024) examined guided inquiry learning (where teachers provide structured scaffolding to support inquiry) in chemistry. They found that guided inquiry learning was particularly effective for supporting conceptual understanding while managing cognitive load students received enough structure to avoid excessive extraneous load while retaining the active mental engagement benefits of inquiry.

Problem-based learning (PBL), where students learn through solving authentic, complex problems, also has substantial chemistry education evidence. Gazali et al. (2025) conducted a systematic literature review on the application of PBL in chemistry education, examining studies from 2015 onward. Their synthesis identified positive effects of PBL on chemistry conceptual understanding, problem-solving skills, and motivation. From a neuroscience perspective, PBL engages multiple cognitive mechanisms: working memory processes (holding problem constraints, solution steps, intermediate results), attention (focusing on problem-critical information), executive function (planning solution strategies, evaluating approaches), and representation (constructing mental models of chemical systems and processes). PBL also typically involves collaboration, which provides external cognitive support (peers can help maintain problem representations in working memory) and opportunities for elaboration (explaining reasoning to peers strengthens memory encoding).

Theme 2: Multiple Representations and Multimedia Learning

Multiple representation systems and multimedia learning represent major foci in chemistry education research and have direct grounding in neuroscience principles. Permatasari et al. (2022) reviewed chemistry learning using multiple representations and identified that systematic approaches to multiple-representation instruction where students learn to translate between macroscopic, submicroscopic, and symbolic representations through structured activities improve conceptual understanding, especially when representations are coordinated progressively rather than presented simultaneously in overload conditions.

Menno & Prodjosantoso (2025) examined the role of chemistry learning multimedia in enhancing cognitive abilities and learning interest. They identified that multimedia (combining text, images, animation, interactive elements) can support chemistry learning when designed according to cognitive principles: (1) Segmentation complex concepts broken into manageable steps; (2) Progressive complexity building from simple to complex; (3) Modality presenting information through complementary modalities (verbal and visual) rather than redundantly; and (4) Interactivity allowing learners to control pace and sequence. When multimedia violates these principles (e.g., presenting too much information simultaneously, using animation at fixed speed despite student comprehension variations), it can actually impair learning by imposing excessive cognitive load. Islamiati & Redhana (2025) examined e-modules in chemistry learning. E-modules, as digital learning resources, can incorporate multiple representations and interactive features. Their review identified that e-modules improve chemistry learning when they: (1) are well-organized and clearly structured; (2) integrate multiple representations thoughtfully; (3) provide interactive practice opportunities; and (4) offer feedback on student understanding. These features align with cognitive principles of working memory management, selective attention, and active learning.

Theme 3: Cognitive-Load-Informed Instructional Design

Gkintoni et al. (2025) critically examined cognitive load theory and educational neuroscience in the context of redefining learning efficacy. They argue that cognitive load theory provides a neurobiologically grounded framework for instructional design: because working memory is limited, instruction should be designed to minimize extraneous cognitive load (information not directly supporting learning) while managing intrinsic load (inherent complexity of the concept). In chemistry, this translates to pedagogical practices such as: (1) Scaffolding providing external support (problem solution steps, worked examples, organizers) that can be gradually faded as competence develops; (2) Sequencing presenting information in optimal order, often from simpler components to more complex integrated systems; (3) Signaling using design features (color, arrows, highlighting) to direct attention toward critical information; and (4) Worked examples demonstrating problem-solution processes so students need not generate every step from scratch, preserving working memory resources for understanding rather than problem-solving process.

Several chemistry education studies applied these principles. Permatasari et al. (2022) identified that sequencing multiple representations presenting them progressively rather than simultaneously reduces cognitive load while maintaining representation integration benefits. Satari et al. (2024) reviewed game-based approaches in chemistry education and found that games can reduce cognitive load while increasing engagement when designed to: (1) present chemistry content in manageable chunks; (2) provide immediate feedback so students can self-correct; (3) allow repeated practice without penalty; and (4) adjust difficulty dynamically based on student performance.

Theme 4: Learning Outcomes Achievement, Understanding, and Engagement

Across the included studies, several learning outcomes were consistently reported when neuroscience-informed practices were implemented: Conceptual Understanding. Multiple studies (Jegstad, 2024; Adauyah & Aznam, 2024; Gazali et al., 2025; Permatasari et al., 2022) reported that inquiry-based learning, guided inquiry, problem-based learning, and multiple-representation instruction improved chemistry conceptual understanding. Conceptual understanding the ability to explain phenomena using chemical reasoning, recognize conceptual relationships, and transfer learning to new contexts represents the highest-level learning outcome and is most sensitive to instructional quality.

Achievement and Test Performance. Achievement, measured through written assessments, improved in most studies employing neuroscience-informed practices (Menno & Prodjosantoso, 2025; Gazali et al., 2025). Effect sizes varied, but multiple studies reported statistically significant improvements with medium to large effects. Critical Thinking and Problem Solving. Rushiana et al. (2023) synthesized evidence that chemistry instruction focused on developing critical thinking engaging students in reasoning about mechanisms, evaluating explanations, and solving complex problems improved critical thinking skills and problem-solving ability. These outcomes reflect higher-order cognitive processes supported by executive function development.

Motivation and Engagement. Affective outcomes also showed improvement. Menno & Prodjosantoso (2025) reported enhanced learning interest and motivation when multimedia was designed for cognitive efficiency and engagement. Gazali et al. (2025) noted that problem-based learning increased motivation, potentially because students perceived chemistry learning as more meaningful and connected to authentic problems. Satari et al. (2024) found that game-based chemistry learning increased engagement.

Neuroscience and Chemistry Learning: An Integrated Framework

This systematic review establishes that neuroscience and cognitive science provide valuable frameworks for understanding chemistry learning processes and informing chemistry instruction. Neuroscience highlights fundamental characteristics and constraints of human cognition, including memory capacity, attentional processes, and the relationship between cognitive mechanisms and task demands (Gkintoni et al., 2025; Nau et al., 2024; Sridhar et al., 2023). At the intermediate level, cognitive mechanisms such as working memory, attention, cognitive load, mental representation, and executive function provide explanatory pathways through which these principles can be understood in learning contexts (Gkintoni et al., 2025; Sridhar et al., 2023; Baker et al., 2022; Kang et al., 2022). Chemistry learning involves multiple cognitive operations, including receiving and encoding information, selectively attending to relevant features, maintaining and manipulating information in working memory, constructing mental representations, reasoning about chemical phenomena, and solving problems (Sridhar et al., 2023; Baker et al., 2022; Permatasari et al., 2022; Rushiana et al., 2023). Chemistry education practices can subsequently be interpreted as applications of these cognitive and neuroscience-informed principles.

Inquiry-based learning promotes active engagement with knowledge construction (Jegstad, 2024; Adauyah & Aznam, 2024), while multiple representations support the coordination of different forms of chemical information and the construction of conceptual understanding (Baker et al., 2022; Permatasari et al., 2022; Yohana et al., 2022). Similarly, multimedia-based instruction can support cognitive processing and manage the demands placed on learners' cognitive resources (Gkintoni et al., 2025; Menno & Prodjosantoso, 2025), whereas active learning and instructional support can facilitate deeper engagement with learning tasks (Dubinsky & Hamid, 2024). Ultimately, improved learning outcomes including conceptual understanding, academic achievement, critical thinking, problem solving, and engagement may emerge when instructional demands are appropriately aligned with learners' cognitive capacities and supported through suitable pedagogical strategies (Jegstad, 2024; Rushiana et al., 2023; Menno & Prodjosantoso, 2025; Dubinsky & Hamid, 2024).

Chemistry as a Domain of Distinctive Cognitive Demands

The review illuminates why chemistry learning benefits from neuroscience-informed perspectives. Chemistry is not unique among sciences in requiring student learning of abstract, unobservable phenomena. However, the integration of multiple representation systems macroscopic, submicroscopic, and symbolic—creates particularly demanding cognitive requirements. Unlike biology, where students often begin with observably complex organisms and gradually descend to cellular and molecular levels, or physics, where mathematical representations often parallel perceptual experience, chemistry demands simultaneous coordination of three distinct representational systems from the beginning. This coordination requirement imposes substantial working memory load and requires sophisticated attention management to maintain coherence among representations. Neuroscience principles help explain both the difficulty students experience in chemistry and potential pathways to more effective instruction.

From Cognitive Mechanisms to Pedagogical Implications

The synthesis reveals clear connections between cognitive mechanisms and pedagogical practices. Working memory constraints have important implications for the use of scaffolding and sequential presentation. Because working memory has limited capacity for maintaining and manipulating information, instructional designs that impose excessive cognitive demands may hinder learning, particularly when learners must simultaneously process multiple sources of complex information (Gkintoni et al., 2025; Sridhar et al., 2023). Conversely, scaffolding through solution templates, worked examples, and step-by-step guidance can provide external support for cognitive processing and reduce unnecessary demands on working memory (Gkintoni et al., 2025; Dubinsky & Hamid, 2024). In chemistry education, sequential presentation of multiple representations such as introducing macroscopic, submicroscopic, and symbolic representations in a structured sequence may facilitate processing by allowing learners to engage with individual representations before integrating them (Permatasari et al., 2022; Yohana et al., 2022). This is particularly relevant because chemical understanding requires learners to coordinate different forms of representation rather than simply process them independently.

Selective attention has similarly important implications for signaling and directed attention. Because attentional processing is constrained and influenced by task demands, instructional materials need to guide learners toward information that is conceptually relevant (Nau et al., 2024; Sridhar et al., 2023). In chemistry education, signaling features such as highlighting, arrows, annotations, and other visual cues can therefore be used to direct learners' attention toward critical features of chemical representations. Evidence from eye-tracking research in chemistry education further supports the importance of examining how learners distribute visual attention when processing chemistry learning materials (Chen, 2025). As learners develop greater expertise, their attention may become increasingly oriented toward conceptually meaningful rather than merely perceptually salient information, suggesting that instructional support for attention allocation may contribute to the development of more effective information-processing strategies (Nau et al., 2024; Chen, 2025).

Cognitive load provides another important basis for instructional design. Cognitive-load-informed instruction emphasizes reducing unnecessary or extraneous processing demands, managing the complexity of learning tasks, and supporting learners in engaging meaningfully with instructional information (Gkintoni et al., 2025). In chemistry education, these principles can be translated into carefully designed multimedia, clearly organized instructional materials, progressively sequenced curricula, and active learning tasks that provide appropriate cognitive support (Menno & Prodjosantoso, 2025; Dubinsky & Hamid, 2024). Rather than simply reducing the amount of information presented, the objective is to align the complexity of instructional tasks with learners' cognitive capacities and provide appropriate support for processing and integration.

Mental model construction also highlights the importance of multiple-representation instruction. Neuroscience and cognitive research emphasize the role of representation in how information is structured, processed, and understood (Baker et al., 2022). In chemistry, learners must construct integrated mental models across macroscopic phenomena, submicroscopic structures and processes, and symbolic representations. Multiple-representation instruction can support this process when representations provide complementary information, learners explicitly practice translating between representations, and the relationships among representations are made clear (Permatasari et al., 2022; Yohana et al., 2022). Thus, the effectiveness of multiple representations depends not simply on increasing the number of representations but on how effectively their relationships are coordinated and cognitively supported.

Finally, executive function development has implications for inquiry, problem-based learning, and reasoning tasks. Executive functions such as inhibitory control, planning, and cognitive flexibility are closely associated with higher-order cognitive processes and the regulation of goal-directed behavior (Kang et al., 2022). Inquiry-based and problem-based learning provide opportunities for learners to engage in cognitively demanding activities involving planning, reasoning, evaluation, and problem solving (Jegstad, 2024; Adauyah & Aznam, 2024; Rushiana et al., 2023). In chemistry education, reasoning tasks that require learners to explain mechanisms, evaluate alternative explanations, and construct solutions may therefore provide opportunities for the application and development of higher-order cognitive processes. Conversely, instructional approaches that rely exclusively on predetermined step-by-step solutions may provide fewer opportunities for learners to independently plan, reason, and evaluate alternative solutions. This suggests that effective chemistry instruction should balance cognitive support with opportunities for productive cognitive effort, rather than simply minimizing cognitive demands.

Multiple Representations as a Keystone of Chemistry Learning

Multiple representations emerge from this review as particularly central to neuroscience-informed chemistry education. Chemistry fundamentally requires representing the same phenomena at different scales and using different symbol systems. Neuroscience evidence that: (a) different representational modalities engage partially distinct neural systems; (b) learning benefits from multiple sensory channels when they provide complementary information; and (c) mental models develop through coordinating information from multiple sources supports the use of multiple representations. However, the review also illuminates cognitive challenges of multiple representations. Simultaneous presentation of multiple representations can impose excessive cognitive load, especially for novice learners. Uncoordinated representations that do not clearly relate to each other may confuse rather than clarify. Successful multiple representation instruction appears to involve: progressive complexity (starting with simpler representations), explicit connections (making links between representations clear), and guided practice (supporting students in translating between representations). These design principles align with cognitive load theory and working memory research.

The integrated neuroscience-chemistry education framework has several direct implications for practitioners: First, chemistry educators should deliberately consider cognitive demands when designing instruction. What cognitive processes does the learning task require? What working memory load will the task impose? Which representational systems must students coordinate? Are prerequisite mental models in place, or must they be developed? Explicitly attending to cognitive demands allows educators to anticipate difficulties and design support accordingly. Second, scaffolding and gradual complexity increase should be systematic. Rather than assuming students can manage multiple representations simultaneously from the start, progressive complexity beginning with simpler representational systems, ensuring mastery before adding additional representations respects working memory constraints while building understanding systematically. Third, multimedia and visualization tools should be designed according to cognitive principles. Features such as animation speed control (allowing learner pacing), progressive disclosure (revealing information step-by-step), and strategic cueing (directing attention) reflect neuroscience-based principles of cognitive management and can enhance learning.

Fourth, active learning approaches inquiry, problem-based learning, and reasoning-focused instruction should be incorporated not merely as pedagogical preferences but as cognitive necessities. These approaches engage the active mental processing that neuroscience indicates is essential for deep learning and executive function development. Fifth, explicit instruction in representation translation should be included. When students explicitly practice translating between macroscopic observations, submicroscopic models, and symbolic equations, they develop fluency in coordinating these representation systems fluency that supports both understanding and problem-solving. Despite the promising synthesis, the review reveals several significant research gaps that warrant future investigation:

Limited Direct Neuroscience Evidence. Most of the included studies employed educational approaches grounded in cognitive theory but did not include direct measures of neural function (e.g., neuroimaging, electrophysiology) or neurocognitive measures (e.g., event-related potentials, functional magnetic resonance imaging). Future research combining educational interventions in chemistry with neurocognitive measurement approaches could provide direct evidence of how neuroscience-informed instructional practices affect neural processing and learning-related brain changes.

Limited Longitudinal and Developmental Evidence. Most included studies examined learning outcomes at single time points. Longitudinal research examining how neuroscience-informed instruction affects learning trajectories over extended periods, and developmental research examining how effectiveness varies across ages and expertise levels, could strengthen understanding of optimal instruction timing and developmental appropriateness. Limited Direct Investigation of Multiple Representations. While multiple representations are extensively studied, few studies examine neurocognitive mechanisms underlying representation integration—e.g., how working memory capacity constrains representation learning, what attention patterns optimize representation processing, or how mental models integrate multiple representational information. Limited Cross-Cultural Evidence. The included studies, while geographically diverse, showed concentration in certain regions. Future research should examine whether neuroscience-informed instructional principles generalize across cultures or whether cultural factors, educational contexts, and prior learning experiences modify effectiveness.

Need for Randomized Controlled Trials. While the included studies demonstrated diverse methodological rigor, experimental evidence remains limited. Rigorously controlled experimental studies comparing neuroscience-informed and conventional instruction in chemistry, with random assignment and careful outcome measurement, could establish causal evidence for instructional effectiveness. Limited Investigation of Individual Differences. Future research should examine how working memory capacity, prior knowledge, cognitive styles, and other individual differences modify the effectiveness of neuroscience-informed chemistry instruction, potentially enabling personalized or adaptive approaches.

Limitations of the Review

Database Selection. Scopus was selected as the primary source, which provided comprehensive coverage but may not capture all relevant literature. Discipline-specific databases (e.g., ERIC for education, PubMed for neuroscience) might have identified additional studies. However, a two-database strategy risks introducing different inclusion criteria across databases. Publication Bias. Like all systematic reviews, this review only examined published studies. Publication bias the tendency for statistically significant findings to be published more readily than null findings may have inflated observed effect sizes and effectiveness estimates.

Language Restriction. The restriction to English-language publications may have excluded relevant non-English literature, particularly from non-Anglophone countries. While this limitation reduces linguistic burden, it potentially introduces geographic bias. Distinction Between Brain-Based Learning and Neuroscience Evidence. The review distinguished between studies grounded in cognitive neuroscience evidence versus those merely using "brain-based learning" terminology without neuroscience support. Some included studies employed pedagogical approaches without explicit neuroscience grounding but were included because they addressed relevant cognitive mechanisms. This requires readers to recognize that pedagogical effectiveness does not automatically imply neuroscience evidence, though neuroscience provides explanatory frameworks. Heterogeneity of Study Designs and Outcomes. The included studies employed diverse designs and measured diverse outcomes. While this diversity enriches understanding, it limits quantitative synthesis and makes precise effect size estimation difficult.

Conclusions

Addressing RQ1: The review identifies clear connections between neuroscience and cognitive processes underlying chemistry learning. Working memory constraints, selective attention, cognitive load, mental representation, and executive function all significantly influence chemistry conceptual understanding and problem-solving. Chemistry learning, with its distinctive requirement to integrate multiple representation systems, exemplifies how cognitive limitations and capacities shape learning. Neuroscience provides explanatory frameworks for understanding why students struggle with chemistry (working memory overload when coordinating representations) and how to support learning more effectively (reducing extraneous load, directing attention, providing scaffolding, supporting mental model construction).

Addressing RQ2: The review identifies multiple pathways through which neuroscience-informed principles translate into chemistry education practices with positive learning outcomes. Inquiry-based and problem-based learning engage active mental processes and support executive function development. Multiple representation instruction, when designed according to cognitive load principles, supports mental model integration. Multimedia and visualization tools, designed to manage cognitive load and direct attention appropriately, enhance learning. Scaffolding and sequencing, grounded in working memory principles, make complex chemistry concepts more learnable. These practices, when implemented thoughtfully according to neuroscience-cognitive principles, produce improvements in conceptual understanding, achievement, critical thinking, problem-solving, and motivation. Integrating these findings reveals a coherent conceptual framework: Neuroscience identifies fundamental constraints and capacities of human cognition; cognitive mechanisms constitute the intermediate level linking neuroscience to learning; chemistry learning processes represent specific applications of cognitive mechanisms in chemistry contexts; neuroscience-informed educational practices optimize alignment between task demands and cognitive capacities; and improved learning outcomes reflect this optimization. This framework integrates previously disparate research traditions educational neuroscience and chemistry education into a unified understanding that is both theoretically grounded and practically applicable.

For chemistry educators, this framework provides guidance for principled instructional design that moves beyond pedagogical fads to grounding decisions in evidence about how human cognition works. For chemistry education researchers, it identifies urgent gaps where neurocognitive approaches could strengthen understanding of learning mechanisms and intervention effectiveness. For neuroscience and cognitive science, it demonstrates how these disciplines can provide genuine insight into domain-specific learning challenges and solutions. Future research should employ neurocognitive measurement methods, examine individual differences in how neuroscience-informed instruction affects learning, employ longitudinal designs to examine learning trajectories, investigate mechanisms of multiple representation integration, conduct rigorous experimental trials, and examine generalization across cultural and educational contexts. As these research gaps are addressed, the neuroscience-chemistry education integration will become increasingly robust and actionable.

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