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EDITED BY
Miriam Segura,
University of North Georgia, United States

REVIEWED BY
Zhengsi Chang,
The University of Texas at Dallas,
United States
Ella Tour,
University of California, San Diego,
United States

*CORRESPONDENCE
Jennifer E. Schaefer
jschaefer@csbsju.edu

†These authors have contributed equally to this work and share senior authorship

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A novel instructional activity using neuroscience core concepts as a pedagogical tool to improve contextualization of primary research articles

Rachael M. Hannah[1†] and Jennifer E. Schaefer[2*†]

[1]Department of Biological Sciences, University of Alaska Anchorage, Anchorage, AK, United States,
[2]Department of Biology, College of Saint Benedict and Saint John's University, Collegeville, MN, United States

Reading primary literature is beneficial for STEM students but, as novice learners, they struggle to integrate research into larger knowledge frameworks and to apply findings beyond a narrow scope. Best practices for teaching primary scientific literature often emphasize development of conceptual knowledge, scientific process competency, or affective goals rather than the goal of contextualizing research. We hypothesized that a novel pedagogical intervention leveraging neuroscience core concepts would improve students': (1) ability to connect primary research articles to broader knowledge contexts, and (2) metacognitive strategies for contextualizing primary research articles. Preliminary qualitative scoring indicated that the intervention improved students' linking of primary research articles to larger conceptual frameworks and that the intervention was more effective when embedded in ongoing pedagogical use of core concepts. Student reflections on their learning processes indicated that they primarily leveraged core concepts for metacognitive declarative knowledge and metacognitive information management strategies. Given that core concepts are published for a variety of STEM fields, findings are of interest to a range of STEM instructors. This work builds on a growing collective effort to implement disciplinary core concepts into accessible, scalable teaching methods, emphasizing engagement with primary scientific literature.

KEYWORDS

STEM higher education, core concepts, neuroscience, primary literature, pedagogy

1 Introduction

Reading primary literature is a cornerstone of STEM education, with numerous benefits for students. Engaging with primary research articles enhances students' understanding of scientific content, providing a deeper and more nuanced grasp of the material (Abdullah et al., 2015), improves scientific reasoning and process skills, and fosters a deeper appreciation of the methodologies and analytical frameworks that underlie scientific research (Gottesman and Hoskins, 2013). By reading primary literature, students enhance their critical thinking and analytical skills, equipping them with the tools necessary for rigorous scientific inquiry (Segura-Totten and Dalman, 2013). Despite these benefits, students often face significant challenges when reading primary research articles. They struggle with understanding complex content at a novice level, have limitations in grasping the scientific process and reasoning, and find it difficult to integrate research findings into broader frameworks and existing understandings (Southard et al., 2016; Hubbard et al., 2022; Flowers et al., 2023). This cognitive demand and difficulty in contextualizing findings limit students' ability to apply research insights beyond a superficial level (Hubbard et al., 2022; Goudsouzian and Hsu, 2023).

This educational activity addresses these challenges through an innovative approach that integrates disciplinary core concepts into the teaching of primary literature, specifically within the context of neuroscience (Chen et al., 2023). The overarching goal of this intervention is to enhance students' ability to connect course content and primary scientific research to broader knowledge contexts (Segura-Totten and Dalman, 2013). Furthermore, this activity emphasizes the importance of students' metacognitive strategies (Tanner, 2012; Stanton et al., 2015, 2021). By promoting practice with task-specific metacognitive strategies, the intervention aims to help students better contextualize and internalize primary literature.

2 Pedagogical framework

2.1 Primary literature in STEM higher education

Teaching students to read primary literature involves several key strategies aimed at developing conceptual knowledge, enhancing competency in the scientific process, and addressing affective goals. First, developing conceptual knowledge requires an instructional focus on helping students understand core principles and theories underlying scientific research. This foundational knowledge enables students to better grasp the significance of research findings (Segura-Totten and Dalman, 2013; Abdullah et al., 2015). Enhancing scientific process competency involves teaching students how to critically evaluate methodologies, interpret data, and understand the nuances of scientific experimentation and reasoning (Gottesman and Hoskins, 2013; Segura-Totten and Dalman, 2013). Addressing affective goals, as emphasized by Goudsouzian and Hsu (2023), includes fostering students' motivation, confidence, and interest in engaging with primary literature. However, these strategies continue to have limitations in developing student abilities to integrate primary research article findings into broader conceptual frameworks. While they help students gain specific skills and knowledge, they do not guide students to connect individual research findings to larger, interdisciplinary knowledge structures. This gap highlights the need for innovative approaches that promote deeper, more integrative learning experiences.

2.2 Disciplinary core concepts

Disciplinary core concepts provide a framework for addressing the challenges of integrating primary literature into broader knowledge frameworks. Core concepts, as defined by Wiggins and McTighe (2005) and Niemi and Phelan (2008), represent foundational principles or "big ideas" that span across subdisciplines within a field. They serve as organizing structures that help students make sense of complex information and facilitate transfer of understanding from one context to another (Michael, 2022; Doherty et al., 2023). By grounding instruction in core concepts, educators can help students build more cohesive and comprehensive knowledge structures. Students often struggle to apply their knowledge to new and varied contexts, which is essential for achieving true mastery of a subject (Kaminske et al., 2020). This difficulty underscores the importance of pedagogical strategies that support transfer of learning.

This novel educational activity leverages neuroscience core concepts (NCCs) as frameworks to help students contextualize primary research article findings. Using NCCs as a learning tool should help students create knowledge frameworks that more effectively incorporate new information (Chen et al., 2023). The eight published NCCs are: Communication Modalities, Emergence, Evolution, Gene–Environment Interactions, Information Processing, Nervous System Functions, Plasticity, and Structure–Function Relationship (Chen et al., 2023).

2.3 Metacognitive learning strategies

The importance of metacognitive learning strategies is central to this activity. Many students enter college with limited awareness of effective learning strategies (Pintrich, 2002). Teaching task-and course-specific metacognitive strategies equips students to monitor and regulate their own learning processes, enhancing self-regulated learning (Nietfeld et al., 2006; Stanton et al., 2015; Dye and Stanton, 2017). Higher-level cognitive strategies are also crucial for helping students transfer their learning and apply their understanding to new problems or broader contexts (Anderson and Krathwohl, 2001). The intervention's use of NCCs connects to the work of Semilarski et al. (2022) and Avargil et al. (2018), who emphasize the role of disciplinary core ideas in enhancing students' metacognitive awareness and self-regulated learning. By embedding NCCs into contextualization tasks, the intervention encourages students to link course content and primary research articles to broader disciplinary knowledge, reinforcing the principles of iterative exposure and active engagement (Owens and Tanner, 2017; Abraham et al., 2019).

We hypothesized that leveraging NCCs in this novel intervention would improve students' ability to: (1) connect course content and primary scientific papers to broader knowledge contexts in neuroscience, and (2) employ metacognitive strategies for contextualizing primary literature. These goals are grounded in educational research showing that integrating metacognitive skills with disciplinary concepts facilitates deeper learning and supports the transfer of knowledge to new contexts.

3 Learning environment and pedagogical format

Sixty total participants were recruited from two courses over three semesters (UAA Neurophysiology BIOL A413 and CSBSJU Neurobiology BIOL 320). All students enrolled in both courses were invited to participate and opted-in via informed consent (fall 2022 BIOL A413 $n = 18$; spring 2023 BIOL 320 $n = 24$; fall 2023 BIOL 320 $n = 18$). The project was exempted by both institutional IRBs. BIOL A413 enrollment consists primarily of junior and senior Biological Sciences or Natural Sciences majors and Neuroscience minors, with a small proportion of graduate students enrolled through cross-listing at the 600-level. UAA is a Carnegie M1 (Master's Colleges & Universities: Larger Programs) Institution and the only open-enrollment public institution in Alaska, enrolling 11,947 students in Fall 2023. The UAA student body is 11.1% multirace and 47% non-White. 91% of UAA students are Alaska residents, 58% are non-traditional (25+ years old), and 58% attend part-time while balancing family and professional responsibilities. BIOL 320 enrollment consists primarily of junior and senior Biology majors, Biochemistry majors, and Neuroscience minors. CSBSJU is a primarily-undergraduate, residential, Benedictine Catholic, liberal arts institution in the U.S. Midwest enrolling approximately 3,000 students. Approximately 80% of CSBSJU students are white and 20% are students of color or international.

In all three semesters and both courses, students read multiple primary research articles. Each time, they answered the following contextualization prompt as part of the written assignment associated with the primary research article: "*How does this research fit into the broader picture of neuroscience beyond this particular paper? For example: What big concepts or ideas does this research help us understand about the physiology of a nervous system (this could be any organism's nervous system)? Your discussion should be broader than a specific disease or condition.*"

The core concept intervention was delivered each semester after students had already answered the contextualization prompt (see above) for one primary research article. The intervention was an in-class activity in which students were asked to reconsider their answer to the contextualization prompt using the framework of the NCCs. The instructions for the activity were: "*Map the paper onto the most relevant neuroscience core concepts. Brainstorm with at least one other student which core concepts the paper fits into and why. Compare the mapped core concepts to your answer [to the prompt]. Revise your answer.*" Students formed groups of 2–3 and discussed which NCCs were most represented in the primary research article, citing specific examples and evidence from the article. During this time, the instructor circulated throughout the room to field questions and provide guidance. Following identification of the NCCs, each student proposed revisions to their original answer to the contextualization prompt. After 15–20 min of small group and independent work, the groups shared the NCCs that they identified, along with rationale, to the class.

Iterative revision varied the timing at which NCCs were introduced relative to reading primary research and implementing the intervention activity, as well as how regularly NCCs were included in class discussions throughout a semester (Table 1). In fall 2022, NCCs were introduced concurrently with the intervention activity after reading the first primary article. Hereafter, this approach is referred to as "single introduction pedagogy." Preliminary data analysis and instructor observations indicated that students needed more exposure to NCCs to effectively use them as a learning tool. This aligns with research in science education (Owens and Tanner, 2017; Zakrajsek, 2022) and cognitive learning mechanisms (Abraham et al., 2019) highlighting the necessity of repeated exposures to disciplinary concepts for effective learning, prompting revisions in subsequent semesters.

In spring and fall 2023, the intervention adopted an "embedded pedagogy" approach. NCCs were introduced earlier in the semester and integrated into instruction throughout, aligning with literature demonstrating the benefits of linking disciplinary core ideas to student metacognition (Semilarski et al., 2022; Avargil et al., 2018). As new course content was introduced, NCCs were used to frame topics through both explicit identification of key NCCs in course notes and opportunistic comments during class discussions. For example, if a student asked clarifying questions about the difference between voltage-gated sodium vs. voltage-gated potassium channel inactivation, the instructor might capitalize on the question to integrate the Structure–Function Relationship NCC into the discussion. After reading and answering the contextualization prompt for the first primary article, students engaged in informal peer discussions about the relevant NCCs during class. The instructor-guided intervention

TABLE 1 Comparison of single introduction vs. embedded pedagogy for neuroscience core concepts (NCCs) within a 15-week course.

	Timing	Single introduction (fall 2022)	Embedded (spring 2023, fall 2023)
Timing of primary research articles and NCC intervention	Week 2		Introduced NCCs as framework for course content
	Week 3	First round of primary literature with contextualizing prompt (**"pre-intervention")	First round of primary literature followed by peer discussion of relevant NCCs
	Week 8		Second round of primary literature with contextualizing prompt (**"pre-intervention") Followed by in-class NCC intervention
	Week 9	Introduction of NCCs In-class NCC intervention using pre-intervention paper	
	Week 11	Second round of primary literature with contextualizing prompt (**"post-intervention")	Third round of primary literature with contextualizing prompt (**"post-intervention")
	Week 14		Fourth round of primary literature with contextualizing prompt (**"post-intervention 2")
NCC integration into course		Limited to a single NCC intervention after reading the first paper	Continuously included to frame course topics throughout weeks 2–14
Student engagement		One-time discussion of NCCs with peers	Encouraged ongoing discussion with peers regarding connection between course topics and NCCs
Activities/Intervention		In-class intervention tied NCCs to reading and contextualizing one paper	Multiple class discussions, course topics, and primary research papers with contextualization prompts applied NCCs as learning framework

Iterative revision to the pedagogy embedded earlier and ongoing NCC discussions in spring and fall 2023 compared to fall 2022. **indicates responses scored as contextualizing prompt response.

was then implemented after the second article (Table 1). This iterative redesign aimed to leverage findings suggesting that embedding concepts into ongoing discussion enhances metacognition and supports self-regulated learning (Avargil et al., 2018; Owens and Tanner, 2017). By regularly engaging students with NCCs, the embedded pedagogy approach aligned with best practices for fostering deeper conceptual understanding and metacognition.

4 Preliminary analysis and results to-date

4.1 Contextualization of primary literature

Student responses to the contextualization prompt were scored for one primary article read prior to the intervention ("pre-intervention" paper) and for articles read after the intervention ("post-intervention" paper) to understand whether the intervention improved contextualization of primary research, particularly for contextualization into NCCs. The single introduction pedagogy included one post-intervention paper while the embedded instruction pedagogy included two post-intervention papers.

Preliminary analysis of the contextualization prompt responses collected to-date is described below. A random sample of contextualization prompt responses were inductively scored by both investigators to produce the following scale:

- 0: no connection to any NCC, little context/evidence provided

Example: *The fifth cranial nerve or the trigeminal ganglion (TG) plays a huge role in the sensory and motor functions of the face, not just sensation of pain. When the TG is damaged many functions of the face such as chewing, speaking and numbness can occur … Research on the physiology and anatomy of this nerve is critical to understanding many motor functions of the face and sensations of pain or numbness. Palsy, trigeminal neuralgia, and headaches can arise from TG damage as well as many other disorders.*

- 1: moderate/weak context evidence, not explicitly tied to a NCC (but answer implicitly describes a concept idea)

Example: *This research is very important to neuroscience in a broader sense because of the ideas and new information about how neurons work, specifically with the communication between presynaptic and postsynaptic neurons. Chemicals and receptors play a big role in the function of the nervous system and so using different studies to test how those receptors work is essential to finding out more information about function and process that goes on within the nervous system.* (core concept Communication Modalities implicit, weak evidence)

- 2: proficient rationale/evidence but no explicit statement of NCC (implicit description) for multiple NCCs, or states NCC but moderate/weak rationale for multiple NCCs, or only 1 NCC addressed

Example: *In a broader neuroscience perspective, how can experimenting with neural plasticity and density change research on psychiatric and neurological disorders? There is question about whether disorders such as depression are truly chemical imbalances as previously suggested. Further research into neural plasticity and "re-wiring" the brain may have a significant impact on the path to find treatments and cures*. (core concept Plasticity explicit)

- 3: explicitly states NCC, with proficient rationale, for >1 NCC

Example: *I found two major core concepts… The first being gene-environment interactions. The correlation between the chemotherapy treatment which comes from the environment and how it fundamentally alters the function of the Nav1.7 channel seems to be an example of how our nervous system can respond to outside elements by changing the way it functions. I think this is also an example of plasticity because the changes in the Nav1.7 in response to both the paclitaxel and the ProTxII blocker show that the nervous system has the ability to not only be altered but for those effects to be reversed back to their original state.* (core concepts Gene-Environment Interactions and Plasticity explicit)

To produce this scale, sample responses were read by both investigators and compared against the NCCs. From that comparison, the 0–3 scale was developed based on alignment with NCCs and clarity of rationale. The scale was designed to evaluate the meaning of a response, rather than specific vocabulary, because we were more interested in students' ability to connect primary research to big ideas than in their ability to apply NCC terminology. This approach was important given that pre-intervention responses were collected prior to NCC introduction under single introduction pedagogy. After the scale was developed, a small set of sample responses were scored collaboratively to ensure consistent application of the criteria. All remaining responses were then scored separately by each investigator, with any scoring differences discussed and resolved to consensus. Given the preliminary nature of this analysis, future work may benefit from further refinement and validation of the scale.

Finally, note that there is not a one-for-one relationship between a primary research article and a "correct" NCC. Most primary research articles can be connected to multiple NCCs, and an instructor may choose to highlight specific connections depending on course goals (Chen et al., 2023; Schaefer and Michael, 2024). Therefore, contextualization responses were not scored for "correct" or "incorrect" core concept connections but rather for meaning and logical connection. As such, the intervention and prompt should be generalizable to most primary research articles.

Preliminary analysis indicates that intervention was successful in improving student contextualization of research into NCC big ideas. Regardless of the pedagogy, individual students either maintained ($n = 23$) or improved ($n = 38$) the contextualization score post-intervention compared to pre-intervention (Figure 1). Only four students decreased scores after the intervention. The mean improvement in score in the single introduction pedagogy was $+0.53 \pm 0.14$ SE ($n = 19$; median = +0). The mean improvement in score in the embedded pedagogy was $+0.91 \pm 0.21$ SE ($n = 39$; median = +1). The improvement in score under the single introduction pedagogy was not significantly different from the improvement in score under the embedded pedagogy ($p = 0.14$; Cohen's $d = 0.37$). Conversely, Figure 2 summarizes each pedagogy separately, reflects the entire set of responses rather than tracking individual students, and separates the two post-intervention papers in the embedded pedagogy. Both intervention pedagogies were successful in that there were fewer 0 scores and a higher proportion of 3 scores after

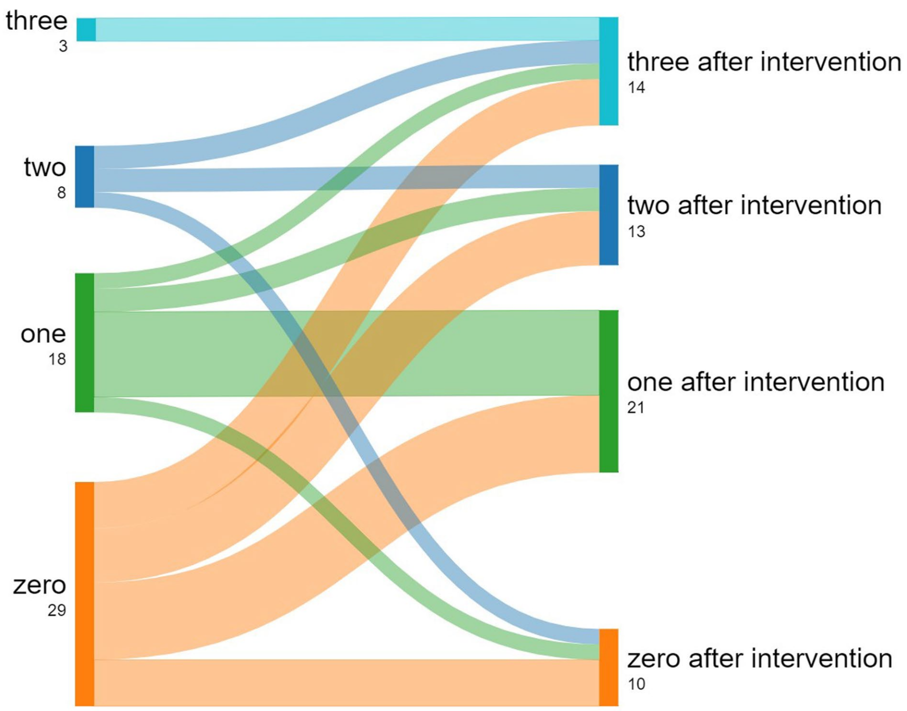

FIGURE 1
Individual students' longitudinal improvement of primary research article contextualization into conceptual frameworks after NCC intervention. Counts indicate numbers of individual responses at each score. Lines trace individual student scores post-intervention (right) relative to pre-intervention score (left). In semesters when students were assigned more than one post-intervention contextualization prompt (see Table 1), the highest score was used as the post-intervention score. Only students who submitted both a pre-intervention response and a post-intervention response are included in these data.

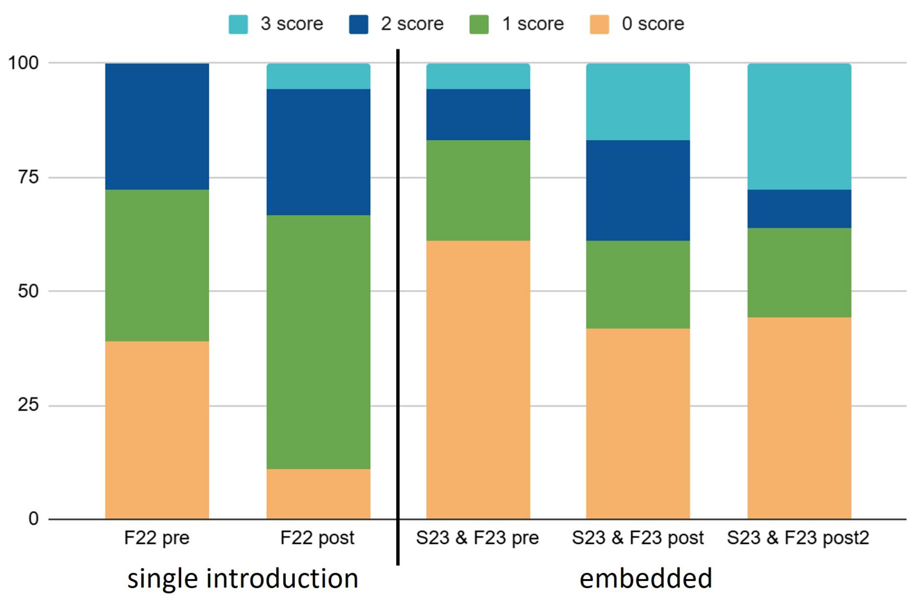

FIGURE 2
NCC intervention improved overall contextualization of primary research articles under both single instruction and embedded pedagogy. Stacked bars indicate percent of total responses at each score. 0 scores became less common and 3 scores became more common under both single introduction and embedded pedagogy. Embedded pedagogy included two post-intervention primary papers, indicated as post and post2 (fall 2022 *n* = 19; spring and fall 2023 *n* = 39).

intervention, with increasingly higher proportions of 3 scores for each post-intervention paper in the embedded pedagogy (Figure 2). Under single introduction pedagogy, 38.9% of the responses scored 0 and 0% of the responses scored 3 prior to the intervention. Post-intervention, 11.1% of responses scored 0 and 5.6% of responses scored 3. Under embedded pedagogy, 61.1% of the responses scored 0 and 5.6% of the responses scored 3 prior to the intervention. Post-intervention, 44.4% of responses scored 0 and 27.8% of responses scored 3.

4.2 Metacognitive processes for reading primary literature

To examine whether and how students used NCCs in their metacognitive processes, students were asked to reflect on their learning with the following prompts in end-of-semester written reflection assignments. The prompt was revised for clarity and directness after fall 2022. We acknowledge that changing the prompt adds complexity to comparing reflection responses. However, we prioritized clarity over consistency of prompt in the interest of student learning. Further, revision to the prompt aligns with the iterative approach to the intervention.

- F22: *Please provide evidence to how you are building your skills to align your new knowledge with neuroscience core concepts?*
- S23 & F23: *How are you building your skills for acquiring new knowledge using neuroscience core concepts? Please provide examples or evidence.*

We describe the preliminary analysis of metacognitive reflections below. Reflections were qualitatively scored by both investigators with deductive coding using *a priori* codes derived from Metacognitive Awareness Inventory (Schraw and Dennison, 1994) metacognitive knowledge and regulation components (Table 2), Codes included: declarative knowledge, procedural knowledge, conditional knowledge, planning (regulation), monitoring (regulation), information management (regulation), debugging (regulation), and evaluation (regulation). Statements of the general value of NCCs for reading primary literature without tying the NCCs to the students own studying generally indicated metacognitive knowledge. For example, statements that NCCs are a useful strategy for a particular reading goal or task, but without indication of how or whether a student implemented the strategy, indicated procedural metacognitive knowledge. Metacognitive regulation codes were generally applied to statements indicating how a student actively employed NCCs in their own reading and learning. For example, explanations of how a student applied NCCs during their own learning to check their understanding indicated metacognitive monitoring. Detailed explanation and examples of coding are provided in Supplementary Table S1.

The investigators independently scored fifteen samples followed by discussion to consensus. All responses were then independently scored, again followed by discussion to consensus for any discrepancies. Examples are provided below. Italicized passages are followed by bracketed descriptions of scoring for the passage.

- I think the neuroscience core concepts have helped me *clarify what sorts of questions we look to answer {identification of what is important = declarative}. Things such as looking at the structure/function relationship … allow for a better frame through which to look at studies. By having a basis of the core concepts, we are able to gain a better idea of what sorts of things studies are trying to answer and it makes reading new studies easier overall {statement of purpose = procedural}.*
- The core concepts *encourage me to carefully think through the results of the studies we read and assess whether they fit {identification of what is important = declarative}, so I am thinking about them in a more thorough way {actively checking comprehension = monitoring}. After the Revah study, I found connections to information processing and emergence that I would not have without using them as a checklist {in addition to monitoring indicated throughout response, this adds a statement of purpose= procedural}.*
- One core concept I have used is the Structure-Function Relationship. I used this core concept to learn the structure of what brain region or area we are focused on and then relate the structure or location of the region to its function. *This was key because it was easier to understand content when I could relate the structure to a specific input or output {actively integrating new information into existing frameworks = information management}.*

When considering all reflections, regardless of whether responses linked those processes to NCCs, students most commonly described declarative and procedural knowledge components of metacognition as well as regulation strategies pertaining to information management (Table 2).

We then examined the degree to which NCCs were represented in the reflections and whether the reflections differently referenced NCCs under embedded vs. single introduction pedagogies. In fall 2022, of students who submitted reflections, 22% referenced NCCs under single introduction pedagogy ($n = 18$), while 46 and 72% of reflections referenced NCCs in spring 2023 ($n = 13$) and fall 2023 ($n = 18$), respectively (Figure 3). When students referenced NCCs in their reflections, we examined what types of metacognitive processes they leveraged the NCCs toward. NCCs were most commonly tied to declarative knowledge processes and to information management (regulation) strategies.

5 Discussion

The primary objective of this educational activity was to enhance students' ability to contextualize primary research within broader neuroscience themes. Students read and critically assessed both seminal and contemporary research papers, learning to understand

TABLE 2 Total number and proportion of student metacognitive reflection responses that described each metacognitive process included in the *a priori* codes (columns).

	Knowledge			Regulation				
	Declarative	Procedural	Conditional	Planning	Monitoring	Information management	Debugging	Evaluation
Total	43	17	3	8	5	22	0	0
Proportion	0.88	0.35	0.06	0.16	0.10	0.45	0.00	0.00

Data do not consider whether responses referenced NCCs. Counts (top row) and percentages (bottom row).

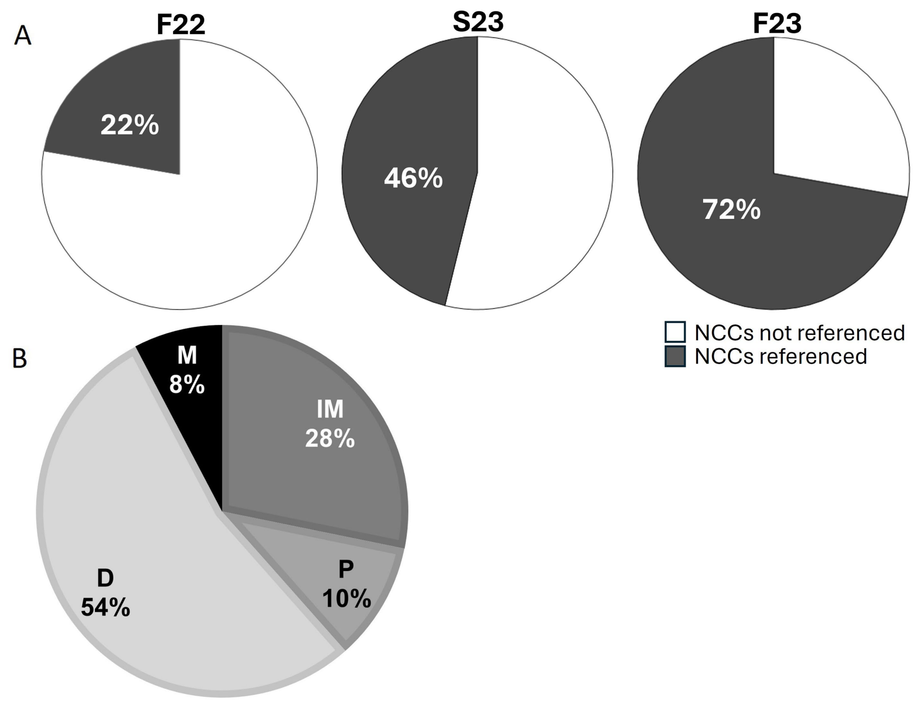

FIGURE 3
Metacognitive reflections referencing NCCs increased with iterative revision to the intervention pedagogy across semesters and were most tied to declarative knowledge and information management strategies. Only students who submitted a metacognitive reflection are included in the data (fall 2022 $n = 18$; spring 2023 $n = 13$; fall 2023 $n = 18$). **(A)** Grey indicates reflections that referenced NCC as important for learning. White indicates reflections that did not reference NCCs. **(B)** Metacognitive processes described in responses that did reference NCCs (grey in **A**) are coded for types of metacognition. D: declarative knowledge, P: procedural knowledge, M: monitoring (regulation), IM: information management (regulation).

experimental design, methodology, results, and implications. They identified gaps in the literature and formulated questions for future research while engaging in discussions about the impact of recent advancements in the field of neuroscience. We employed NCCs developed by Chen et al. (2023) as a learning framework to aid contextualization of the primary papers. For instance, when students read a research paper on how latent virus infections like COVID-19 contribute to neurodegenerative diseases, NCCs help them relate the research to nervous system functions that coordinate survival responses and maintain homeostasis. Classroom observations and student submissions from a single intervention in Fall 2022 revealed a challenge: one discussion and exercise using NCCs were insufficient for students to consistently apply them as a learning tool for contextualizing primary literature (Figure 2). This observation aligns with educational research (Owens and Tanner, 2017; Zakrajsek, 2022) and insights from cellular learning mechanisms (Abraham et al., 2019), which suggest the necessity of multiple exposures to reinforce learning. To address this gap, we revised our approach in Spring and Fall 2023 by introducing NCCs earlier and incorporating NCCs into multiple exercises (Table 1). This iterative design aligned with prior research supporting the need for repeated exposure to concepts and competencies to develop higher-order cognitive skills (Anderson and Krathwohl, 2001; Zakrajsek, 2022).

Given that this is a preliminary study, additional analysis and data collection is warranted. The subjective nature of content analysis and qualitative scoring, despite efforts to reach consensus, introduces potential bias and is a constraint of the study. Instructors considering implementing this intervention in their own classes should note that this was not a controlled experimental design. Nevertheless, the preliminary results suggest a positive impact of the intervention on the students' metacognitive strategies. Most students either maintained or improved their contextualization scores post-intervention compared to pre-intervention (Figure 1). While both the single introduction pedagogy and the embedded instruction pedagogy showed effectiveness, the embedded approach resulted in a higher proportion of 3 scores on the contextualization prompt post-intervention (Figure 2). Within the embedded pedagogy, when students contextualized more than one post-intervention paper, their scores on the contextualization prompts often varied (data not shown). To account for this variability, we tracked individual student improvement using the higher of the two post-intervention scores (Figure 1). This approach aligns with the understanding that learning trajectories are rarely linear, and that metacognitive skill development often occurs through iterative and uneven progress (Pintrich, 2002; Zimmerman, 2002). Although achieving full mastery of contextualization requires sustained longitudinal improvement, using the highest score as a measure of competency reflects the students' ability to demonstrate metacognitive strategies effectively under the embedded pedagogy. This finding underscores the importance of repeated exposures and iterative practice, as supported by metacognitive learning literature (Nietfeld et al., 2006; Dye and Stanton, 2017), to foster deeper and more consistent skill development.

Notably, the sentiment of the concept, rather than the precise title of the concept, played a significant role in scoring. Many students with lower scores in their pre-intervention responses were not simply unfamiliar with the exact terminology—they failed to express the underlying ideas or sentiments entirely, resulting in scores of 0. This observation aligns with educational research emphasizing that novice learners often struggle to engage deeply with disciplinary core concepts until they develop foundational knowledge and familiarity with the frameworks of the discipline (Semilarski et al., 2022; Avargil et al., 2018). In the third round of embedded pedagogy contextualization scoring, some students framed their responses around ethical considerations as key big ideas given the nature of the primary article, but did not explicitly address either the sentiment or title of a NCC. This finding highlights the integrative nature of ethical reasoning as a competency that spans across all NCC areas, echoing literature on the value of linking disciplinary core concepts with competencies like ethical reasoning and critical thinking (Owens and Tanner, 2017). Such integration fosters students' ability to connect theoretical concepts with broader societal and scientific contexts, a key goal of education in the sciences. Future studies should include detailed statistical analysis to validate our preliminary findings regarding the effectiveness of the intervention. Such analyses could contribute to a more robust understanding of how targeted educational interventions enhance learning outcomes in science education.

The second aim of the intervention was to improve students' metacognitive skills related to reading primary literature, equipping them to engage with such material more effectively in the future. By developing these skills, students can better manage their learning processes, fostering improved integration and synthesis of primary research article findings. Explicitly framing NCCs as a learning tool that students should use for contextualizing primary research aligns with educational literature emphasizing that explicit instruction in metacognitive strategies supports self-regulated learning and enhances students' ability to apply knowledge in novel contexts (Pintrich, 2002; Zimmerman, 2002). This is in line with a finding by Semilarski et al. (2022) that involving students in building disciplinary and interdisciplinary core idea maps—using mind mapping and concept mapping—can promote perceived self-efficacy in learning science. Qualitative analysis of metacognitive reflections indicated that students primarily focused on declarative knowledge (metacognitive knowledge) and information management strategies (metacognitive regulation) when describing metacognitive approaches that relied on NCCs. This finding is consistent with research by Nietfeld et al. (2006) and Stanton et al. (2015), which highlight the importance of both knowledge and regulation components of metacognition for meaningful learning. Further, the embedded pedagogy increased student references to NCCs in their metacognitive reflections (Figure 3). As students became more adept at using NCCs, they described improvements in both metacognitive knowledge and metacognitive regulation around reading complex primary literature. This progression aligns with Dye and Stanton's (2017) emphasis on iterative and scaffolded learning to develop metacognitive skills. Students reported that embedding NCCs in their learning process allowed them to move beyond isolated reading and to position research within a broader disciplinary and contextual framework, thereby enhancing comprehension and critical engagement with primary literature (Figures 2, 3).

The data represents two distinct educational settings: upper-division neurobiology and neurophysiology courses at the University of Alaska Anchorage (UAA) and the College of Saint Benedict and Saint John's University (CSBSJU). UAA, a Carnegie M1 institution, is an open-enrollment public university with a diverse student body of 11,947 students, 47% of whom are non-White and many of whom balance family and professional responsibilities. In contrast, CSBSJU is a primarily undergraduate, residential, Benedictine Catholic liberal arts institution in the Midwest, enrolling approximately 3,000 students, 80% of whom are white. Both courses focus heavily on current neurobiological research and reading primary literature in discussion-based courses. The intervention will need to be evaluated for success in other educational contexts.

Core concepts—fundamental principles spanning various sub disciplines—serve as powerful tools to help students create cohesive knowledge frameworks, enabling them to contextualize and integrate new information into larger scientific narratives (Wiggins and McTighe, 2005; Niemi and Phelan, 2008; Michael, 2022). By grounding students in these foundational ideas, educators can address common challenges that students face when reading primary research, particularly struggles to apply complex concepts to novel contexts. Leveraging core concepts not only enhances students' ability to navigate and synthesize scientific literature but also fosters critical thinking and adaptability, skills essential for success in both academic and real-world scientific endeavors (Kaminske et al., 2020).

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving humans were approved by College of Saint Benedict IRB and University of Alaska Anchorage IRB. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

RH: Conceptualization, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. JS: Conceptualization, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feduc.2025.1481415/full#supplementary-material

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