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Cognitive Processing and Neurodevelopmental Perspectives on Misconceptions in Elementary Science Education: A Comprehensive Analysis

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Abstract: Misconceptions in elementary science education are a persistent challenge embedded in the cognitive architecture and neurodevelopmental trajectories of young learners. This comprehensive analysis examines the phenomenon of science misconceptions in elementary school students through the integrated lens of cognitive processing theory and brain development research. By synthesizing contemporary neuroscience findings with an established cognitive psychology framework, this article elucidates the neurobiological underpinnings of misconception formation, persistence, and potential remediation strategies. The analysis reveals that misconceptions are not simply learning errors but, rather, systematic constructs arising from the interaction of developing neural networks, limited cognitive resources, and intuitive reasoning patterns. Limited prefrontal cortex maturity, working memory constraints, and a tendency toward intuitive thinking create a developmental context in which misconceptions naturally emerge. Next, the article explores how neurodevelopmental factors (such as synaptic pruning and executive function development) influence the process of conceptual change. By testing various theoretical frameworks, including conceptual change theory and the dual-process model of cognition, in a neurodevelopmental context, this work provides educators and researchers with a deeper understanding of why misconceptions persist and how evidence-based instructional strategies aligned with brain development can facilitate more effective conceptual understanding. Implications of this study include curriculum design, teacher training, and assessment practices that respect the developmental realities of elementary school students.

Keywords: Brain development; Cognitive processing; Elementary science education; Misconceptions; Neurodevelopment

Introduction

The landscape of elementary science education is profoundly shaped by a phenomenon that has captured researchers, educators, and cognitive scientists for decades: the prevalence and persistence of misconceptions. These alternative conceptions, sometimes termed naive theories or preconceptions,

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represent systematic patterns of thinking that diverge from scientifically accepted understanding yet remain relatively resistant to traditional instructional approaches (Sukackė et al., 2022; Sun & Zhang, 2022). What makes misconceptions particularly fascinating from a cognitive neuroscience perspective is that they are not random errors or simple gaps in knowledge, but rather coherent cognitive constructions that arise from the fundamental ways in which the developing brain processes, organizes, and makes sense of natural phenomena (Kravchenko & Yudenko, 2025).

Elementary school students arrive in science classrooms not as blank slates but as active sense-makers who have already constructed elaborate explanatory frameworks about the physical, biological, and earth sciences based on their everyday experiences and observations (Cabello et al., 2021; Haverly et al., 2022). A child who observes that heavy objects fall faster than light ones, that summer occurs because Earth is closer to the sun, or that plants obtain food from the soil has constructed these understandings through legitimate cognitive processes that, while scientifically inaccurate, represent rational attempts to explain observable phenomena (Marini et al., 2025). The challenge for science education lies not simply in correcting these errors but in understanding why they form, why they persist even after instruction, and how the developing brain can be supported in reconstructing more scientifically accurate conceptual frameworks (Miranda & Baylon, 2025; Windiyani et al., 2025).

The intersection of cognitive processing theories and neurodevelopmental research provides a uniquely powerful lens through which to examine misconceptions in elementary science education. Recent advances in neuroimaging technologies, including functional magnetic resonance imaging (fMRI) and electroencephalography (EEG), combined with decades of cognitive psychology research (Janssen et al., 2021; Morita et al., 2016), have begun to reveal the neural mechanisms underlying learning, reasoning, and conceptual change. These insights suggest that misconceptions are not merely pedagogical problems to be solved through better explanations or more engaging activities, but are deeply rooted in the architecture and developmental trajectory of the human brain itself (Romero & Castillo, 2025; Tye & Cullen, 2025).

The elementary school years, roughly corresponding to ages five through twelve, represent a critical period of neurodevelopment characterized by dramatic changes in brain structure and function (Lang, 2025; Tooley et al., 2022). The prefrontal cortex, responsible for executive functions including abstract reasoning, cognitive flexibility, and inhibitory control, undergoes substantial maturation during this period. Simultaneously, processes such as synaptic pruning and myelination enhance neural efficiency, while working memory capacity gradually increases (Leisman et al., 2015; Introzzi et al., 2021). These neurodevelopmental changes profoundly influence how children process scientific information, engage in causal reasoning, and manage the cognitive demands of conceptual change. Understanding misconceptions through this neurodevelopmental lens illuminates why certain types of misconceptions are particularly prevalent at specific ages and why instructional approaches must be developmentally appropriate to facilitate genuine conceptual understanding (Nurazizah & Junaidi, 2025; Medina et al., 2023). The purpose of this article is to provide a comprehensive analysis of elementary science misconceptions through an integrated cognitive processing and neurodevelopmental framework. By examining how the developing brain constructs, maintains, and potentially reconstructs scientific understandings, this work aims to bridge the gap between cognitive neuroscience research and educational practice (Kusumaningtyas et al., 2025; Maknun et al., 2025).

The insights generated through this analysis have profound implications for how we design science curricula, train teachers, implement instructional strategies, and assess student understanding in ways that align with rather than work against the neurodevelopmental reality of elementary learners. As we proceed through this analysis, we will explore the theoretical foundations that explain misconception formation from cognitive and neurological perspectives, examine the specific neurodevelopmental factors that influence science learning during the elementary years, investigate the mechanisms of conceptual change and the neural processes involved, and ultimately consider how this integrated understanding can inform more effective and developmentally appropriate approaches to elementary science education. The goal is not simply to catalog misconceptions or their corrections, but to deeply understand their origins in the cognitive and neural architecture of developing learners, thereby enabling educators to work more effectively within the constraints and possibilities of the developing brain.

Method

This method involves a systematic review and synthesis of findings from a variety of disciplines, including cognitive psychology, developmental neuroscience, educational neuroscience, and science education research.

Data Collection

Literature was identified through searches of major academic databases (PubMed, Web of Science, ERIC, Google Scholar) using key terms related to misconceptions, brain development, and conceptual change. Priority was given to peer-reviewed empirical studies (especially those using neuroimaging) as well as influential reviews and theoretical papers.

Analytical Approach

This approach aims to integrate findings to build a multilevel explanation of misconceptions that encompasses neural mechanisms, cognitive processes, and educational manifestations; Convergence Bridge: Synthesis is conducted by seeking converging findings across methodologies (e.g., if neuroscience, cognitive psychology, and educational research all point to the same conclusion, it strengthens the analytical framework); Acknowledgement of Limitations: The inherent limitations of each type of research are acknowledged (e.g., neuroimaging studies show patterns of activation but do not prove a direct causal relationship with behavioral outcomes).

Limitations and Ethics

This approach recognizes its limitations, including the complexity of the relationship between brain structure, cognition, and educational outcomes. This analysis avoids simplistic neural determinism, instead using neuroscientific insights to enrich our understanding of misconceptions without directly prescribing specific teaching methods. To provide context for the scope and nature of misconceptions in elementary science education, the following table summarizes common categories of misconceptions across major science domains, their typical manifestations, and the cognitive processing characteristics that contribute to their formation.

Table 1. Common Science Misconceptions in Elementary Education and Associated Cognitive Processing Factors

Science Domain	Common Misconception Examples	Cognitive Processing Factors	Neurodevelopmental Considerations
Motion & Forces	Heavy objects fall faster; Force is needed for constant motion; Objects at rest have no forces acting on them	Perceptual dominance; Limited abstract reasoning; Intuitive physics based on direct experience	Developing prefrontal cortex limits abstract force conceptualization; Parietal regions processing motion rely on sensory-motor integration
Energy	Energy is used up; Energy is a fuel; Only moving things have energy	Concreteness bias; Difficulty with conservation concepts; Limited causal reasoning	Abstract concept processing limited by frontal lobe maturation; Working memory constraints affect multi-step reasoning
Living Systems	Plants get food from soil; Breathing is the same as respiration; Humans evolved from modern apes	Teleological reasoning; Anthropomorphic thinking; Limited systems thinking	Temporal reasoning challenges related to hippocampal development; Theory of mind networks influence anthropomorphic attributions
Heredity	Acquired characteristics are inherited; Dominant traits are more common; All offspring are identical to parents	Limited probabilistic reasoning; Essentialism; Direct causation bias	Abstract probability concepts exceed working memory capacity; Essentialist thinking linked to categorization systems
Seasons	Summer occurs when Earth is closer to the sun; Seasons are the same everywhere	Egocentric perspective; Difficulty with spatial reasoning; Limited scale comprehension	Spatial processing in parietal lobes still developing; Perspective-taking limited by prefrontal maturation
Earth Systems	Earth is flat or bowl-shaped; Gravity only pulls down; Clouds are made of cotton	Perceptual primacy; Geocentric reasoning; Limited model-based thinking	Conflict between perceptual and conceptual systems; Abstract model manipulation limited by cognitive development

Source: Synthesized from multiple research studies including Vosniadou & Brewer (1992), Driver et al. (1994), and recent neurocognitive research on science learning (Masson et al., 2014; Potvin et al., 2015)

This analysis reveals that misconceptions are not distributed randomly across science content but cluster around concepts that require abstract reasoning, counter-intuitive thinking, understanding of systems and processes occurring beyond perceptual access, and integration of multiple interacting variables. These are precisely the cognitive demands that challenge developing brains with immature prefrontal cortices, limited working memory capacities, and neural systems still undergoing fundamental organizational changes.

Result and Discussion

The integrated analysis of misconceptions in elementary science education through cognitive processing and neurodevelopmental lenses reveals a complex, multi-layered phenomenon that cannot be adequately understood through any single disciplinary perspective. The results of this synthesis illuminate why misconceptions are so prevalent, why they persist despite instruction, and what implications this has for educational practice. This section presents key findings organized thematically, examining neurodevelopmental foundations, cognitive processing mechanisms, specific types of misconceptions through this integrated lens, and implications for conceptual change.

Neurodevelopmental Foundations of Misconception Vulnerability

The elementary school years represent a period of dramatic neurodevelopmental change that fundamentally shapes how children process and understand scientific information. The prefrontal cortex, which undergoes protracted development extending into the mid-twenties, plays a crucial role in the higher-order cognitive functions essential for scientific reasoning including abstract thinking, cognitive flexibility, planning, inhibitory control, and working memory. During the elementary years, this region is functionally immature relative to adult levels, which has profound implications for science learning (Jiang et al., 2024; Papadopoulos et al., 2023).

The limited development of the prefrontal cortex during elementary years constrains children's capacity for abstract reasoning, which is essential for understanding many scientific concepts. Scientific understanding often requires reasoning about entities and processes that cannot be directly observed such as atoms and molecules, gravitational fields, energy transformations, or internal biological processes. While concrete operational thinking emerges during the elementary years, allowing children to reason logically about concrete objects and events they have experienced directly, formal operational thinking involving abstract reasoning and hypothetical-deductive logic typically does not emerge until adolescence. This developmental limitation means that elementary students often struggle to construct mental models of scientific phenomena that involve unobservable entities or abstract principles (Laliyo et al., 2023; DeSutter & Stieff, 2017).

The consequence is that elementary students tend to rely heavily on perceptual features and concrete observations when constructing explanations of natural phenomena. Misconceptions that arise from this concrete reasoning bias include beliefs that heavy objects fall faster because they "look like" they should fall faster based on everyday experience, that matter disappears when it dissolves because it is no longer visible, or that the sun moves across the sky because this matches perceptual experience. The developing brain, constrained by limited abstract reasoning capacity, constructs explanations grounded in what can be directly observed, which often leads to scientifically inaccurate conclusions about phenomena where the underlying causal mechanisms are not perceptually accessible.

Working memory capacity shows substantial development across the elementary years but remains limited compared to adolescent and adult levels. Young elementary students typically can hold and manipulate about three to four chunks of information simultaneously in working memory, with this capacity gradually increasing across middle childhood. This limited capacity creates a significant bottleneck for scientific reasoning, which often requires coordinating multiple variables, tracking multi-step causal chains, or simultaneously considering both observable phenomena and underlying theoretical mechanisms. When the cognitive demands of a scientific explanation exceed available working memory resources, students resort to simpler explanatory schemes that may be scientifically inaccurate but manageable within their cognitive constraints.

For example, understanding seasonal changes requires simultaneously considering Earth's revolution around the sun, the tilt of Earth's axis, the relationship between axis tilt and the angle at which sunlight strikes different parts of Earth's surface, and how this angle affects the amount of solar energy received per unit area. Coordinating all these elements places substantial demands on working memory. The misconception that seasons result from changing distance from the sun is much simpler, requiring only the intuitive understanding that being closer to a heat source makes you warmer. While scientifically incorrect, this explanation is cognitively economical, placing minimal demands on working memory resources.

Inhibitory control, the ability to suppress prepotent but inappropriate responses, shows dramatic improvement across the elementary years but remains less developed than in older individuals (Tinello et al., 2023; Carriedo et al., 2025). Neuroimaging studies have demonstrated that children show less activation in prefrontal regions associated with cognitive control and more activation in brain regions associated with the prepotent response, suggesting that inhibition requires greater effort and is less reliably successful in children than adults. The relevance to science misconceptions is that many misconceptions represent intuitive responses that feel compelling and are rapidly generated by Type 1 cognitive processes. Overcoming these misconceptions requires inhibiting the intuitive response while constructing and activating a more scientifically accurate but less intuitive explanation (Liu et al., 2024; Potvin & Cyr, 2017).

Research has demonstrated that even when students learn scientifically correct explanations, the neural representations of misconceptions remain present and must be actively inhibited. Studies using interference paradigms show that verification of scientifically correct statements takes longer when they conflict with common misconceptions compared to when they align with intuitive understanding, suggesting that additional cognitive control is required to inhibit the competing misconception. For elementary students with developing inhibitory control systems, this inhibition is particularly challenging and effortful, which explains why misconceptions can resurface when cognitive resources are depleted or when students encounter problems in contexts different from instruction.

The development of causal reasoning abilities during elementary years also influences misconception formation. Young children show limited understanding of probabilistic causation, preferring deterministic explanations where a cause invariably produces an effect. They also show difficulty reasoning about causal chains involving multiple intermediate steps, particularly when some steps involve unobservable processes. The preference for direct, simple causation leads to misconceptions in domains like heredity, where probabilistic mechanisms and multi-step processes are fundamental, or in understanding disease transmission, where intermediate steps in infection processes are not directly observable.

Synaptic pruning and myelination, fundamental processes of brain development occurring throughout the elementary years, shape the efficiency and organization of neural networks involved in learning and reasoning (Mualem et al., 2024). Synaptic pruning eliminates unused neural connections while strengthening frequently used ones, resulting in more efficient neural processing. Myelination increases the speed of neural transmission by insulating axons with myelin sheaths. These processes enhance cognitive efficiency but also create a form of neural commitment, where frequently activated neural patterns become increasingly entrenched. This has implications for misconceptions: conceptual frameworks that are frequently activated through everyday experience become neurally entrenched, making them more difficult to modify or override even when scientifically incorrect.

Cognitive Processing Mechanisms Underlying Misconception Formation

Beyond developmental factors, specific cognitive processing mechanisms contribute to misconception formation and persistence. The dual-process account of reasoning provides a powerful framework for understanding why misconceptions arise and persist. Type 1 intuitive processes generate rapid responses based on perceptual features, similarity to familiar situations, and heuristics that generally work well in everyday contexts. These processes are cognitively efficient, requiring minimal attention and working memory resources, and they operate largely automatically and unconsciously. Type 2 analytical processes involve deliberate, effortful reasoning that requires substantial cognitive resources, operates slowly, and demands conscious attention and working memory resources.

Many science misconceptions arise directly from Type 1 intuitive processing. The intuitive physics that underlies everyday object manipulation generates misconceptions about force and motion. For example, the intuitive belief that constant motion requires continuous force arises from everyday experience where friction and air resistance require continuous effort to maintain motion. This intuitive understanding works perfectly well for most everyday situations but conflicts with Newton's first law, which requires the more abstract understanding that constant motion in the absence of friction requires no force. Similarly, the belief that seasons result from changing distance from the sun arises from the intuitive understanding based on direct experience that proximity to a heat source affects temperature.

The challenge in science education is that Type 2 analytical thinking, required to construct and reason with scientifically accurate concepts, demands cognitive resources that are limited in elementary students (Arifin et al., 2025; Morris, 2025). Even when students successfully engage analytical thinking during instruction, the default Type 1 intuitive responses do not disappear. These competing responses remain and can resurface when cognitive resources are limited, when problems are framed in ways that trigger intuitive responses, or when students are under time pressure or cognitive load. This explains the common observation that students can correctly answer questions on tests immediately following instruction but revert to misconceptions when encountering similar concepts in different contexts or after a delay.

Neuroimaging research supports this dual-process account by demonstrating that scientific reasoning activates prefrontal regions associated with cognitive control and inhibition, suggesting that successful scientific reasoning requires suppressing intuitive responses. Studies have shown that individuals who achieve correct scientific understanding show greater activation in dorsolateral prefrontal cortex and anterior cingulate cortex, regions associated with cognitive control, error detection, and conflict resolution. This neural evidence suggests that scientific reasoning is not simply a matter of learning new information but requires active cognitive control to override intuitive but incorrect responses (Dawson et al., 2024).

Cognitive heuristics, mental shortcuts that allow rapid decision-making with limited information, also contribute to misconception formation. The representativeness heuristic leads individuals to judge probability based on similarity to prototypical examples rather than on actual statistical principles. This heuristic contributes to misconceptions about inheritance, such as the belief that dominant traits must be more common in populations because "dominant" sounds like it should mean "more prevalent." The availability heuristic, judging likelihood based on how easily examples come to mind, contributes to misconceptions about weather and climate, where recent memorable weather events overly influence understanding of climate patterns.

The curse of knowledge effect, well-documented in cognitive psychology, creates challenges for both learners and teachers in science education. This effect refers to the difficulty that experts have in imagining the perspective of novices once they have acquired expertise. Teachers who have achieved scientifically accurate understanding may struggle to recognize how compelling intuitive misconceptions feel to students, leading them to underestimate the difficulty of conceptual change. Students, in turn, may believe they understand scientific concepts when they have merely memorized terminology without achieving genuine conceptual understanding, because they cannot accurately assess the depth of understanding required for scientific expertise.

The role of language and linguistic framing in misconception formation has been increasingly recognized. Many everyday expressions embed scientifically inaccurate conceptualizations. We speak of the sun rising and setting, reinforcing a geocentric perspective. We talk about plants eating or drinking, suggesting that plants obtain energy similarly to animals. We describe energy as being used up or consumed, reinforcing the misconception that energy is a substance that can be depleted rather than conserved through transformation. These linguistic patterns, which students encounter constantly in everyday communication, compete with scientific language and conceptualizations introduced in formal instruction.

Mental models and their limitations also contribute to misconception patterns. Students construct mental models to represent scientific phenomena, but these models are often incomplete, inconsistent, or based on inappropriate analogies. For example, students might model the atom as a miniature solar system with electrons orbiting the nucleus like planets orbit the sun. While this model captures some features of atomic structure, it is scientifically problematic because it treats electrons as discrete particles following defined trajectories rather than as quantum entities described by probability distributions. Such models based on inappropriate analogies can both support initial learning and create barriers to more sophisticated understanding.

The ontological categorization framework proposed by Chi provides insight into why certain misconceptions are particularly resistant to change. Some misconceptions involve placing phenomena into fundamentally incorrect ontological categories. For example, treating heat as a substance (the caloric theory) rather than as energy transfer involves a fundamental categorical error. Understanding electric current as a substance that flows through wires rather than as a coordinated movement of electrons involves similar categorical confusion. Correcting these misconceptions requires not simply learning new information but recategorizing phenomena into entirely different ontological classes, which is a cognitively demanding form of conceptual change that challenges developing cognitive systems.

Specific Misconception Domains Through Cognitive-Neurodevelopmental Lens

Examining specific domains of science misconceptions through the integrated cognitive-neurodevelopmental lens reveals how different types of misconceptions arise from different combinations of developmental constraints and cognitive processing patterns. In physics education, particularly regarding force and motion, misconceptions are widespread and persistent. The belief that heavier objects fall faster, that objects in motion have force while objects at rest do not, or that constant motion requires constant force all reflect intuitive physics grounded in everyday experience with friction and air resistance. From a neurodevelopmental perspective, these misconceptions persist because they are generated by Type 1 intuitive processes based on perceptual-motor experience, and correcting them requires abstract reasoning about forces and motion in idealized conditions without friction, which demands prefrontal cognitive resources that are limited in elementary students (Finley, 2025).

Energy concepts present particular challenges because energy is an abstract quantity that cannot be directly observed, only inferred from its effects. The misconception that energy is used up or consumed reflects a concrete reasoning bias where students focus on observable outcomes rather than abstract conserved quantities. Energy transformations require tracking multi-step causal processes where energy changes form while total quantity remains constant, placing substantial demands on working memory. The developing brain's preference for concrete, observable phenomena over abstract conserved quantities makes energy misconceptions particularly prevalent during elementary years (Cole et al., 2020).

In biology, teleological and anthropomorphic reasoning patterns contribute to distinctive misconceptions. Young children's tendency to explain natural phenomena in terms of purpose or function leads to beliefs that biological structures exist "in order to" serve particular functions, such as birds having wings in order to fly or plants having leaves in order to make food. While these explanations capture the functional relationship between structure and outcome, they invert the causal story that evolutionary biology provides, where structures exist because they served functions that enhanced reproductive success in ancestors. The teleological reasoning that underlies these misconceptions appears to be a natural way that developing minds impose order on observations, but it conflicts with mechanistic biological explanations.

Anthropomorphic attribution of human-like characteristics, intentions, and emotions to plants and animals is prevalent among young children and contributes to biological misconceptions (Dacey & Coane, 2023; Prato-Previde et al., 2022). Students might explain plant behaviors like phototropism by attributing intentions or desires to plants, or explain animal behaviors by attributing human-like emotions and reasoning. While anthropomorphic thinking can serve as a bridge to more sophisticated understanding, it can also impede development of mechanistic biological explanations if students do not progress beyond attributing intentionality to organisms. The neurodevelopmental trajectory of theory of mind and perspective-taking abilities influences anthropomorphic reasoning patterns, with decreasing anthropomorphism as children develop more sophisticated understanding of different types of minds and mechanistic causation. Understanding heredity and genetics presents challenges rooted in several cognitive limitations.

The probabilistic nature of inheritance conflicts with children's preference for deterministic causation. The multiple-level organization where genes influence traits through complex biochemical processes involving proteins and cellular mechanisms requires tracking causal chains across multiple scales of organization, placing substantial demands on working memory and abstract reasoning. The invisibility of genetic material and cellular processes means students cannot ground understanding in direct perceptual experience. Essentialist thinking, the intuitive belief that category members share some underlying essence that determines their properties, contributes to misconceptions about inheritance including beliefs that organisms must resemble parents in all characteristics or that acquired characteristics can be inherited.

Earth and space science concepts present unique challenges related to scale, perspective, and spatial reasoning. The massive scales involved in astronomical phenomena exceed everyday experience and intuitive comprehension. Understanding the Earth-sun relationship requires coordinating multiple spatial reference frames and overcoming egocentric and geocentric intuitions. The apparent flatness of Earth's surface from human perspective conflicts with its actual spherical shape. The counterintuitive explanation for seasons requiring understanding of axial tilt and its effect on solar radiation angle conflicts with the simpler intuitive explanation based on distance from the heat source.

Spatial reasoning abilities, which show substantial development across the elementary years and rely on parietal cortex regions that are still developing, are taxed by the mental transformations required to understand Earth-space relationships. Perspective-taking, requiring understanding how things appear from viewpoints different from one's own, depends on prefrontal and parietal regions that undergo continued development throughout childhood and adolescence. The cognitive demands of coordinating multiple spatial reference frames, imagining perspectives from space looking at Earth, and mentally representing three-dimensional relationships from two-dimensional diagrams all contribute to the prevalence and persistence of earth-space misconceptions.

Conceptual Change Through Cognitive-Neurodevelopmental Lens

Understanding the neural and cognitive mechanisms of conceptual change provides insights into why misconception correction is challenging and what conditions might facilitate successful change. The traditional view of conceptual change as replacement of incorrect with correct conceptions has given way to a more nuanced understanding where multiple representations coexist and compete. Neuroimaging evidence suggests that even after successful instruction, neural representations of misconceptions remain present and must be actively inhibited when reasoning about scientific concepts. The persistence of these neural representations explains why misconceptions can resurface long after seemingly successful instruction.

Conceptual change appears to involve not simply constructing new neural representations but learning to activate appropriate representations in relevant contexts while inhibiting competing misconceptions (Addido et al., 2022; Naeem Sarwar et al., 2024). This requires developing cognitive control over the competition between intuitive and scientific representations. For elementary students with developing prefrontal cognitive control systems, establishing reliable control over these competing representations is particularly challenging. The gradual development of inhibitory control across the elementary years suggests that capacity for conceptual change involving inhibition of strong intuitive misconceptions should improve with age during this period.

The role of cognitive conflict in promoting conceptual change has been extensively discussed in the education literature, with the idea that students must first become dissatisfied with their existing conceptions before being motivated to construct new understandings. From a neuroscience perspective, detection of conflict or error activates the anterior cingulate cortex, a region involved in monitoring for conflict and signaling the need for increased cognitive control. However, simply experiencing conflict does not guarantee conceptual change. Students must have sufficient cognitive resources available to engage in the effortful process of constructing alternative explanations and sufficient cognitive flexibility to entertain ideas that conflict with strongly held intuitions.

The development of metacognitive abilities during the elementary years influences capacity for conceptual change. Metacognition, the ability to reflect on and regulate one's own thinking, is essential for recognizing when one's understanding is inadequate and needs revision. Students with better metacognitive skills are more likely to recognize inconsistencies in their understanding and to engage in the deliberate effort required for conceptual reconstruction. However, metacognitive abilities show protracted development across childhood and adolescence, with younger elementary students showing limited capacity for metacognitive awareness and regulation.

The emotional dimensions of learning also affect conceptual change processes. Misconceptions that have been held for long periods and that make intuitive sense can become part of students' conceptual identity. Being told that one's understanding is wrong can evoke defensive reactions that impede openness to alternative conceptions. Creating emotionally safe learning environments where mistakes are viewed as learning opportunities rather than failures may facilitate the risk-taking required for genuine conceptual change. Neuroscience research on emotion and cognition demonstrates that emotional states influence cognitive processing, with negative emotions potentially narrowing attention and reducing cognitive flexibility, while positive emotional states can enhance creative problem-solving and openness to new ideas.

The spacing effect, where distributed practice over time produces better long-term learning than massed practice, has implications for conceptual change. Neuroscientific research suggests that memory consolidation, the process by which new memories are stabilized and integrated with existing knowledge, continues over extended periods and is enhanced by repeated retrieval practice spaced over time. Applying this to conceptual change suggests that a single instructional episode, however well-designed, is unlikely to produce stable conceptual change. Rather, repeated engagement with concepts across multiple contexts and over extended time periods may be necessary for scientifically accurate concepts to become consolidated and reliably activated.

The role of explanation and argumentation in conceptual change relates to neurocognitive research on social cognition and communication. When students articulate and defend their reasoning, this engages prefrontal regions involved in language production, working memory, and reasoning. Social interaction around scientific concepts can promote conceptual change by exposing students to alternative perspectives, creating cognitive conflict, and requiring explicit articulation of reasoning that might otherwise remain implicit and unexamined. However, social learning contexts also require managing the social-emotional aspects of disagreement and the risk of being wrong in front of peers, which can create barriers particularly for students who are struggling.

Implications for Elementary Science Instruction

The integrated understanding of misconceptions through cognitive processing and neurodevelopmental perspectives has profound implications for elementary science instruction. First, it suggests that misconceptions should not be viewed as simple errors to be corrected through clearer explanations but as natural products of developing cognitive systems attempting to make sense of complex phenomena with limited cognitive resources. This recognition calls for compassion and patience in working with students struggling with scientific concepts, understanding that their difficulties often reflect neurodevelopmental constraints rather than lack of effort or ability.

Second, instructional approaches should be designed to work within rather than against neurodevelopmental constraints. For elementary students with limited working memory capacity, instruction should minimize extraneous cognitive load by presenting information clearly and simply, avoiding split attention between multiple sources of information, and scaffolding complex reasoning tasks into manageable components. However, reducing cognitive load should not mean oversimplifying to the point of reinforcing misconceptions. Rather, the goal is to carefully sequence instruction to gradually build toward scientifically accurate understanding while managing cognitive demands at each stage.

Third, explicitly addressing common misconceptions rather than ignoring them appears beneficial based on cognitive and neural research. Making misconceptions explicit, discussing why they seem intuitively compelling, and directly contrasting them with scientific explanations can help students recognize the conflict and engage cognitive control processes needed to inhibit misconceptions. However, this must be done carefully, as simply exposing students to misconceptions without adequate support for constructing alternatives could reinforce rather than correct them.

Fourth, instruction should engage students in active sense-making rather than passive reception of information, consistent with neuroscience evidence that meaningful learning involves active construction of neural networks. However, given working memory limitations, active learning should be scaffolded with appropriate guidance rather than expecting students to discover scientific concepts independently. The optimal approach appears to be guided inquiry where students actively investigate phenomena with structured support that prevents cognitive overload while promoting genuine cognitive engagement.

Fifth, recognizing that conceptual change often requires inhibiting intuitive misconceptions suggests that developing inhibitory control and other executive functions may support science learning. Activities that strengthen executive functions, including working memory training, inhibitory control practice, and cognitive flexibility exercises, might indirectly support science learning by enhancing the cognitive resources available for conceptual change. However, the transferability of executive function training remains debated, and direct instruction in science concepts should not be replaced with general cognitive training.

Sixth, the persistent nature of neural representations of misconceptions suggests that repeated engagement with scientific concepts across multiple contexts and over extended time periods is necessary for stable conceptual change. Curriculum design should provide opportunities for students to revisit and build on core concepts across grades rather than treating topics once and moving on. Spiraling curriculum designs that return to fundamental concepts at increasing levels of sophistication may be particularly appropriate given neurodevelopmental progression across the elementary years (Płatos et al., 2025).

Seventh, assessment practices should recognize the distinction between students' ability to reproduce correct explanations and their genuine conceptual understanding. Traditional assessments may overestimate conceptual understanding if they primarily measure recognition or recall of correct information rather than students' spontaneous reasoning about novel problems. Transfer tasks requiring application of scientific concepts in new contexts provide better windows into whether conceptual change has occurred or whether intuitive misconceptions remain the default mode of reasoning. Finally, teacher education should include preparation in cognitive development and the neuroscience of learning, not to expect teachers to become neuroscientists but to provide them with a deeper understanding of why misconceptions arise and persist. Teachers who understand the neurodevelopmental basis of misconceptions may be better equipped to anticipate student difficulties, recognize misconceptions as natural products of developing cognition rather than failures of teaching or learning, and design instruction that works with rather than against the cognitive and neural reality of their students.

Conclusion

Environmental education is not only limited to fostering cognitive environmental awareness in students, but must also be able to develop affective and psychomotor aspects. Based on the results of the literature analysis of studies that highlight local potential in the Gunungkidul area, it is known that various existing environmental issues can be used as contextual and meaningful learning resources. Information from these local potential studies can be used as learning resources to foster knowledge, build awareness, and encourage real student action on environmental issues. In addition, from the analysis of environmental education learning studies, appropriate and relevant approaches, models, teaching materials and learning media were found for students where the results of the studies can be selected, combined and then used to increase the effectiveness of their learning on the topic of environmental change so that there are no longer gaps or inequalities in the student learning process. Thus, student learning outcomes not only become more conceptually meaningful, but also have an impact on the formation of attitudes and skills in maintaining environmental sustainability. This effort is in line with the main goal of environmental education which is to build awareness and action rooted in contextual, transformative and sustainable learning experiences.

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Conceptualization.; methodology.; software.; validation.; formal analysis; investigation.; resources, data curation, M. K; writing—preparation of original draft; writing—review and editing.; visualization; supervision; project administration M.

N.; obtaining funding D. R. All authors have read and agreed to the published version of the manuscript.

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