

Review

The Cognitive Ecology of Learning: Attentional Fragmentation, Cognitive Malnourishment, and Cognitive Endurance in Technology-Rich Secondary Science Classrooms

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Highlights

What are the main findings?

- The Cognitive Ecology of Learning Framework (CELf) organizes three classroom-level dimensions—disciplinary cognitive demand, attentional fragmentation conditions, and restoration opportunities—to examine sustained disciplinary cognition in technology-rich secondary science classrooms.
- CELf proposes that cognitive malnourishment may become more likely when substantial disciplinary or informational demand coincides with persistent attentional fragmentation and insufficient opportunities for elaboration, reflection, consolidation, and coherent reengagement.

What are the implications of the main findings?

- Secondary science instruction may support sustained disciplinary cognition by preserving conceptual continuity, coherent instructional workflows, prolonged inquiry, reflective processing, and opportunities for attentional recovery.
- Educational technology may support deep learning when digital tools advance a coherent disciplinary objective and reduce unnecessary switching, competing stimulation, and repeated cognitive reorientation.

Abstract

Background/Objectives: Contemporary secondary students increasingly learn in technology-rich classrooms characterized by digital stimulation, multitasking demands, compressed pacing, platform switching, and persistent attentional competition. Established scholarship on cognitive load, multimedia learning, self-regulated learning, disciplinary literacy, attentional control, and environmental restoration identifies mechanisms relevant to these conditions, but these mechanisms are often examined at different levels of analysis. This conceptual review develops the Cognitive Ecology of Learning Framework (CELf) as an applied, classroom-level framework for examining how disciplinary cognitive demand, attentional fragmentation conditions, and restoration opportunities may interact during sustained secondary science learning. **Methods:** An integrative conceptual-review and theory-synthesis design was used. Iterative searches conducted from January through May 2026 identified theoretical, empirical, and review literature across education, psychology, attentional science, digital learning, environmental psychology, and secondary science education. Sources were selected purposively according to their relevance to the research questions and synthesized through cross-domain comparison. **Results:** The synthesis proposes CELf as a hypothesis-generating framework organized around three classroom-level dimensions: Disciplinary Cognitive Demand, Attentional Fragmentation Conditions,



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and Restoration Opportunities. The framework also proposes cognitive malnourishment and cognitive endurance as context-sensitive constructs requiring empirical validation. Cognitive malnourishment describes a possible ecological mismatch in which substantial informational or disciplinary demand coincides with persistent fragmentation and insufficient opportunities for elaboration, reflection, consolidation, and coherent reengagement. Cognitive endurance refers to the context-sensitive capacity to sustain attention, conceptual processing, and disciplinary reasoning during extended, cognitively demanding work. Preliminary indicators, measurement approaches, and testable propositions are presented for future classroom-based research. Conclusions: CELF organizes selected task-level, learner-level, disciplinary, attentional, and environmental constructs within a bounded framework for technology-rich secondary science classrooms. It does not revise or replace the foundational theories from which these constructs are drawn, nor does it claim causal validation. Instead, CELF provides a structure for investigating how classroom conditions may support or constrain attentional continuity, conceptual persistence, restoration, and sustained disciplinary engagement.

Keywords: cognitive ecology of learning; attentional fragmentation; cognitive load theory; learning sciences; educational technology; secondary science education; cognitive endurance

1. Introduction

Technology-rich secondary science classrooms increasingly operate amid continual digital stimulation, multitasking demands, rapid task switching, compressed instructional pacing, and recurring competition for students' attention. Educational technologies have expanded access to scientific visualization, inquiry, collaboration, and flexible learning opportunities. At the same time, these environments raise questions about whether repeated attentional interruptions constrain the sustained processing required for biologically secondary knowledge and skills, including disciplinary reasoning, working-memory coordination, and conceptual integration (Geary, 2008; Mayer, 2021; Sweller et al., 2011). Although educational research has examined engagement, instructional efficiency, and technology access extensively, less attention has been directed toward how attentional and environmental conditions accumulate across complex disciplinary-learning experiences.

Secondary science provides a particularly important context for examining these conditions. Students must often coordinate abstract concepts, specialized vocabulary, visual representations, laboratory procedures, evidence evaluation, and explanatory models before their understanding is fully developed (Duschl, 2008; National Research Council, 2012; Osborne, 2010). These activities place substantial demands on working memory and executive attention, especially when reasoning must be maintained across extended periods (Baddeley, 1992; Cowan, 2001; Engle, 2002). Cognitive load theory explains how instructional design can reduce unnecessary demands on limited working-memory resources (Sweller, 1988; Sweller et al., 2011). Meaningful conceptual development also requires sufficient continuity for learners to retrieve prior knowledge, persist through difficulty, reorganize emerging understanding, and construct durable knowledge structures (Bjork & Bjork, 2011; Kapur, 2016; Kirschner et al., 2006). The instructional challenge therefore involves not only managing cognitive demands within a task but also preserving the conditions under which students can remain engaged with those demands long enough to elaborate, revise, and integrate their understanding.

Research on contemporary digital environments suggests that such conditions cannot be assumed. Frequent media multitasking and task switching have been associated with

weaker attentional filtering, reduced sustained focus, and greater vulnerability to competing stimuli during cognitively demanding activities (Ophir et al., 2009; Rosen et al., 2011; Uncapher & Wagner, 2018). Interruptions may also introduce cognitive interference and stress even after learners return to the original task (Mark et al., 2008). Research on digital reading further indicates that some screen-based environments may encourage scanning, abbreviated processing, and weaker comprehension of complex texts, although outcomes vary according to the task, learner, and instructional design (Delgado et al., 2018; Liu, 2005; Mangen et al., 2013; Wolf, 2018). These findings do not establish that educational technology is inherently harmful. Multimedia instruction, simulations, and virtual laboratories can strengthen accessibility, visualization, and inquiry when they direct attention toward relevant conceptual relationships rather than introduce unnecessary competition (de Jong et al., 2013; Mayer, 2021). The central concern is therefore not technology use itself but the attentional conditions produced by instructional environments and digital workflows.

Several established theoretical traditions identify mechanisms relevant to this problem at different levels of analysis. Cognitive load theory examines relationships among instructional demands, learner knowledge, and working-memory limitations. Multimedia learning addresses how verbal and visual information should be organized to support cognitive processing. Self-regulated learning focuses on learners' planning, monitoring, strategy selection, and adaptation, while disciplinary literacy examines the specialized practices required for reasoning, reading, writing, and communicating within a field. Executive-functioning and attentional perspectives identify mechanisms involved in goal maintenance, inhibition, selection, and cognitive reorientation (Diamond, 2013; Posner & Rothbart, 2007). Ecological and environmental perspectives further suggest that cognition and behavior develop through continuing interactions between individuals and their surroundings (Bronfenbrenner, 1979; S. Kaplan, 1995). Educational neuroscience similarly emphasizes the interdependence of cognitive, emotional, social, and environmental conditions during learning (Immordino-Yang et al., 2019), while attention-restoration research examines how directed attention may be influenced by environmental demands and opportunities for recovery (S. Kaplan & Berman, 2010). An applied need remains for organizing these selected mechanisms around the classroom-level conditions associated with sustained disciplinary cognition in technology-rich secondary science settings.

The Cognitive Ecology of Learning Framework (CELf) is proposed as an applied, mid-range organizing framework for examining these conditions. CELf does not revise or replace the foundational propositions of cognitive load theory, multimedia learning, self-regulated learning, executive-functioning research, disciplinary literacy, or environmental psychology. Instead, it draws on selected constructs from these traditions to examine how three classroom-level dimensions—*Disciplinary Cognitive Demand*, *Attentional Fragmentation Conditions*, and *Restoration Opportunities*—may interact during extended secondary science learning. Disciplinary Cognitive Demand refers to the intellectual requirements associated with scientific reading, inquiry, evidence evaluation, conceptual integration, and explanatory reasoning. Attentional Fragmentation Conditions refer to interruptions, competing stimulation, workflow complexity, and repeated cognitive reorientation that may disrupt an active line of disciplinary thought. Restoration Opportunities refer to instructional and environmental provisions for attentional recovery, reflection, consolidation, and coherent reengagement. These dimensions are descriptive classroom-level categories rather than proposed additions to existing psychological taxonomies.

CELf also proposes two context-sensitive constructs: *cognitive malnourishment* and *cognitive endurance*. Cognitive malnourishment describes a possible ecological mismatch in which substantial informational or disciplinary demand coincides with persistent attentional fragmentation and insufficient opportunities for sustained elaboration, reflection,

consolidation, and coherent reengagement. The term describes conditions surrounding learning rather than a student deficit, diagnostic category, or fixed cognitive state. Cognitive endurance refers to the context-sensitive capacity to sustain attention, conceptual processing, and disciplinary reasoning during extended, cognitively demanding work. It is not synonymous with time on task, behavioral compliance, motivation, persistence, or grit. Both constructs are hypothesis-generating and require empirical investigation rather than being treated as established outcomes of technology-rich instruction.

CELf is bounded to technology-rich secondary science contexts and is presented as a conceptual, noncausal, and nondiagnostic framework. Using an integrative conceptual review, the manuscript addresses the following questions:

RQ1. How do cognitive, attentional, environmental, and disciplinary-learning perspectives explain the conditions supporting or disrupting sustained cognition in technology-rich secondary science classrooms?

RQ2. How can selected task-level, learner-level, disciplinary, attentional, and environmental constructs be integrated into a classroom-level framework for examining sustained cognition in technology-rich secondary science classrooms?

RQ3. How can cognitive malnourishment and cognitive endurance be defined, differentiated from related constructs, and operationalized for future research?

RQ4. What testable propositions and instructional-design implications follow from the relationships proposed within CELf?

2. Conceptual Review Methodology

This section describes the integrative conceptual-review methodology used to develop the Cognitive Ecology of Learning Framework. It explains the review design, literature-identification process, source-selection criteria, analytic synthesis, and methodological limitations. The purpose is to make transparent how selected constructs and mechanisms from cognitive psychology, educational psychology, attentional science, environmental psychology, digital learning, disciplinary literacy, and secondary science education were identified and organized into CELf's classroom-level dimensions, emergent constructs, and testable propositions.

2.1. Review Design

An integrative review was selected because the purpose was not to estimate a pooled effect, evaluate a single intervention, or provide an exhaustive account of one bounded body of literature. The review sought to connect theoretical and empirical scholarship across multiple fields, clarify relationships among related constructs, identify mechanisms relevant to sustained disciplinary cognition, and organize those mechanisms within an applied framework suitable for future empirical testing (Jaakkola, 2020; Snyder, 2019; Torraco, 2005).

The review was guided by the four research questions presented in the previous section, which directed the synthesis toward:

- (a) Identifying cognitive, attentional, environmental, and disciplinary perspectives relevant to sustained cognition;
- (b) Determining how selected task-level, learner-level, disciplinary, attentional, and environmental constructs could be organized within a classroom-level framework;
- (c) Defining cognitive malnourishment and cognitive endurance, differentiating them from adjacent constructs, and identifying their proposed boundaries;
- (d) Translating the proposed relationships among CELf's dimensions and emergent constructs into testable propositions and instructional-design implications.

CELF draws on scholarship from several fields, and the review included theoretical, empirical, and research-synthesis publications. Foundational works were used to establish the origins and established meanings of the constructs informing the framework. More recent empirical studies and reviews were used to examine contemporary digital, attentional, environmental, and instructional conditions. The review was conceptual rather than systematic; consequently, it did not employ meta-analysis, formal risk-of-bias scoring, or a PRISMA-based study-selection protocol. The resulting synthesis should therefore be interpreted as a transparent, purposive framework-development process rather than as an exhaustive systematic review of every relevant study.

2.2. Literature Identification

Literature searches were conducted from January through May 2026, culminating in the manuscript's initial submission. Databases were selected to reflect the interdisciplinary scope of the review. ERIC and Education Source were used to identify scholarship on education, secondary science instruction, disciplinary literacy, educational technology, and self-regulated learning. PsycINFO was used to locate research on attention, executive functioning, working memory, cognitive fatigue, motivation, and related psychological processes. Scopus and Web of Science provided broader coverage across cognitive psychology, the learning sciences, environmental psychology, and educational technology. PubMed/MEDLINE was used selectively to identify neuroscience research relevant to attention, cognitive control, memory consolidation, and postencoding rest. Google Scholar supported backward and forward citation searching and assisted in identifying foundational works not consistently indexed across the other databases. No publication-year restriction was applied because the framework required both seminal theoretical sources and contemporary empirical research.

Searches combined terms from four broad concept clusters:

1. Cognitive processes: working memory, executive attention, sustained attention, cognitive load, inhibitory control, memory consolidation, deep processing, and cognitive fatigue;
2. Attentional and environmental conditions: attentional fragmentation, media multitasking, task switching, attention residue, digital interruption, platform switching, classroom noise, environmental stimulation, and attention restoration;
3. Disciplinary learning: secondary science education, disciplinary literacy, scientific reasoning, inquiry learning, evidence evaluation, conceptual change, scientific argumentation, and deep reading;
4. Learner regulation and engagement: self-regulated learning, cognitive engagement, metacognition, persistence, grit, mind-wandering, and executive functioning.

Because several mechanisms relevant to CELF have been examined primarily outside secondary science classrooms, searches were not restricted to adolescent or school-based samples. Research involving adults, laboratory tasks, workplace settings, environmental contexts, and digital-reading conditions was included when it provided evidence concerning a theoretically relevant mechanism, such as task switching, attentional reorientation, environmental stimulation, cognitive fatigue, or restoration. Evidence drawn from these contexts was used to inform construct development rather than to establish direct generalizability to secondary science classrooms. This distinction was maintained throughout the synthesis and is addressed further in the methodological limitations section.

2.3. Selection and Prioritization of Sources

Sources were selected purposively according to their relevance to the research questions and their potential contribution to the conceptual development of CELF. Publications were prioritized when they met one or more of the following criteria:

1. Established or clarified a major theoretical tradition informing the framework;
2. Examined cognitive mechanisms relevant to sustained attention, working memory, task switching, restoration, or conceptual consolidation;
3. Addressed disciplinary practices central to secondary science learning, including inquiry, evidence evaluation, scientific reading, argumentation, and conceptual change;
4. Examined how digital, instructional, or environmental conditions influenced cognitive continuity or academic processing;
5. Differentiated constructs adjacent to cognitive malnourishment or cognitive endurance;
6. Provided measurement approaches, empirical designs, or operational indicators relevant to future CELF research.

Priority was given to peer-reviewed empirical studies, meta-analyses, research reviews, foundational theoretical publications, and authoritative scholarly books or reports. Sources were excluded when they lacked a clear connection to the research questions, addressed technology without considering cognition or learning, focused exclusively on clinical diagnosis without an educational or environmental implication, or duplicated evidence already represented more directly by another source.

Source selection was also guided by the need to maintain conceptual boundaries among CELF’s components. Literature concerning disciplinary task requirements informed Disciplinary Cognitive Demand; research on interruption, switching, competing stimulation, and reorientation informed Attentional Fragmentation Conditions; and scholarship concerning attentional recovery, reflective processing, consolidation, and environmental restoration informed Restoration Opportunities. Literature on cognitive overload, distraction, attentional fatigue, shallow processing, engagement, sustained attention, self-regulation, persistence, and grit was used primarily to differentiate the proposed emergent constructs from adjacent concepts rather than to subsume those established concepts within CELF.

Table 1 summarizes the conceptual domains used to organize the literature search, the representative search concepts associated with each domain, the principal basis for source inclusion, and the role of each domain in the development of CELF.

Table 1. Conceptual domains, representative search concepts, and roles in the CELF development.

Review Domain	Representative Search Concepts	Primary Inclusion Focus	Role in CELF Development
Cognitive architecture and cognitive load	Working memory; cognitive load; executive attention; inhibitory control; selective attention	Theories and studies explaining limited processing capacity, goal maintenance, and task demand	Informed Disciplinary Cognitive Demand and the distinction between productive disciplinary challenge and avoidable processing demands
Digital attention and interruption	Media multitasking; task switching; attention residue; notifications; platform switching; digital interruption	Research on attentional switching, interference, task resumption, and digital competition	Informed Attentional Fragmentation Conditions and the proposed mechanisms through which interruption and reorientation may disrupt conceptual continuity

Table 1. *Cont.*

Review Domain	Representative Search Concepts	Primary Inclusion Focus	Role in CELF Development
Environmental psychology and restoration	Attention restoration; mental fatigue; classroom noise; visual stimulation; postencoding rest; cognitive recovery	Research on environmental demand, fatigue, recovery, reflection, and memory consolidation	Informed Restoration Opportunities as classroom-level provisions for attentional recovery, reflection, consolidation, and coherent reengagement
Secondary science and disciplinary literacy	Science education; disciplinary literacy; inquiry; scientific argumentation; conceptual change; evidence evaluation	Scholarship defining the sustained reasoning and representational coordination required in science	Established the disciplinary context of CELF and specified the forms of sustained cognition represented within Disciplinary Cognitive Demand
Self-regulation, executive functioning, and engagement	Self-regulated learning; metacognition; executive control; cognitive engagement; persistence; grit	Research on learner regulation, monitoring, sustained effort, and engagement	Helped differentiate cognitive endurance from self-regulation, executive functioning, behavioral engagement, persistence, and grit
Deep processing, memory, and expertise	Depth of processing; generative learning; retrieval; memory consolidation; long-term working memory; expertise	Research on elaboration, integration, retention, schema development, and transfer	Supported the conceptual basis of cognitive malnourishment and its distinction from cognitive overload, shallow processing, and isolated learning difficulty
Framework operationalization	Classroom observation; cognitive-load scales; learning analytics; experience sampling; delayed transfer; written explanation	Studies providing measures or research designs adaptable to CELF constructs	Informed preliminary indicators, measurement approaches, propositions, and future empirical designs without treating existing measures as direct measures of CELF constructs

Note. The review domains represent bodies of literature used to identify selected constructs, mechanisms, conceptual boundaries, and potential measurement approaches relevant to CELF. Their inclusion does not indicate that CELF revises, combines, or replaces the foundational theories associated with these domains.

2.4. Analytic Synthesis and Framework Development

The analysis proceeded through three iterative stages. First, sources were organized according to their primary theoretical or empirical contribution: cognitive architecture and cognitive load, attentional control and executive functioning, digital interruption and task switching, disciplinary literacy and science education, environmental psychology and restoration, self-regulated learning and engagement, and memory consolidation and deep processing.

Second, the literature was examined across traditions at the level of selected constructs and mechanisms to identify areas of convergence, conceptual tension, and opportunities for classroom-level organization. Particular attention was given to differences in unit of analysis. Cognitive load and multimedia perspectives generally emphasized processing demands within instructional tasks, executive-functioning and self-regulated-learning perspectives emphasized learner-level regulation, disciplinary-literacy research identified the forms of reasoning required by science, and environmental research examined contextual conditions influencing attention and recovery.

Third, the cross-disciplinary findings were organized into three classroom-level dimensions—Disciplinary Cognitive Demand, Attentional Fragmentation Conditions, and Restoration Opportunities—and two proposed emergent constructs: cognitive malnourishment and cognitive endurance. Construct boundaries were refined by comparing each proposed term with adjacent concepts, including cognitive overload, distraction, attentional fatigue, shallow processing, engagement, sustained attention, self-regulation, persistence, and grit.

The framework propositions were then developed by converting the proposed conceptual relationships into statements that could be supported, refined, or rejected through empirical investigation. Candidate indicators and potentially adaptable measurement approaches were identified by examining methods used in the contributing studies, including cognitive-load ratings, classroom observations, interruption logs, digital trace data, task-resumption measures, think-aloud protocols, written explanations, delayed-retention measures, transfer tasks, experience sampling, and longitudinal performance evidence.

Throughout the synthesis, claims were differentiated according to evidentiary proximity:

- Direct evidence from secondary or classroom-based educational contexts;
- Adjacent evidence from related learning, laboratory, workplace, adult, or environmental contexts;
- Conceptual inference generated through the integration of those studies.

This distinction was used to avoid treating theoretically plausible relationships as empirically established effects in secondary science classrooms.

2.5. Methodological Limitations

Several limitations follow from the review design. First, because the review was integrative and conceptual rather than systematic, it cannot establish that all relevant studies were identified or that the included literature is representative of the full evidence base within each field. Second, the breadth of the synthesis required the inclusion of evidence from heterogeneous populations, tasks, and research settings. Findings derived from adult, workplace, laboratory, digital-reading, and environmental studies may identify plausible mechanisms but cannot independently establish effects in secondary science classrooms.

Third, the organization of the literature and derivation of CELF necessarily involved interpretive judgment. Other researchers might prioritize different theoretical traditions or define the boundaries among Disciplinary Cognitive Demand, Attentional Fragmentation Conditions, Restoration Opportunities, cognitive malnourishment, and cognitive endurance differently. Finally, no formal risk-of-bias assessment or quantitative aggregation was conducted. These limitations reinforce CELF's status as a hypothesis-generating framework and underscore the need for systematic reviews, measurement studies, and direct classroom-based testing.

3. Sustained Cognition and Secondary Science Learning

This section establishes the theoretical foundation for CELF by examining the cognitive systems and disciplinary practices involved in sustained secondary science learning. It first considers working memory, executive attention, and cognitive load before examining the prolonged conceptual and disciplinary processing required in science. It then explains why sustained cognition should be understood as a cognitive process whose continued deployment is shaped by interactions between learners and their instructional environments.

3.1. Cognitive Architecture and Sustained Goal-Directed Processing

Sustained disciplinary learning requires learners to maintain task goals, coordinate information in working memory, inhibit irrelevant stimuli, and direct attention toward conceptually relevant material. Working-memory capacity is limited, particularly when learners must process unfamiliar information or coordinate several representations simultaneously (Baddeley, 1992; Cowan, 2001). Executive-attention research further indicates that successful learning depends not only on the availability of information but also on the learner's ability to preserve goal-directed processing while filtering competing stimuli (Diamond, 2013; Engle, 2002; Posner & Rothbart, 2007). Working memory and selective attention are therefore closely connected because learners must retain relevant information while controlling which internal and environmental stimuli receive continued processing (Baddeley, 2000; D'Esposito & Postle, 2015; Gazzaley & Nobre, 2012).

Cognitive load theory explains how instructional demands interact with these limited cognitive resources. Learning becomes more difficult when task complexity and unnecessary processing demands exceed available working-memory capacity (Sweller, 1988; Sweller et al., 2011). Well-designed instruction can reduce avoidable cognitive competition while supporting the construction of organized knowledge structures. Extraneous demand may also arise from contextual and environmental conditions surrounding the task rather than from instructional materials alone (Taylor et al., 2022).

3.2. Sustained Processing in Secondary Science Learning

Secondary science is a relevant context for examining sustained cognition because much of its content consists of biologically secondary knowledge—knowledge that generally requires explicit instruction, deliberate practice, and extended engagement rather than developing automatically through everyday experience (Geary, 2008). Students must often coordinate specialized vocabulary, abstract relationships, visual models, mathematical representations, laboratory procedures, evidence, and explanatory claims while their conceptual understanding remains incomplete (National Research Council, 2012). Science learning also requires movement among conceptual, epistemic, and social forms of reasoning, including evaluating evidence, constructing explanations, and defending claims (Duschl, 2008; Osborne, 2010). These practices place demands on working memory and executive control because several sources of information must remain cognitively available while learners construct relationships among them.

Cognitive challenge is not inherently detrimental. Desirable difficulties, retrieval, and productive struggle can strengthen long-term learning when students have sufficient support and time to reorganize and apply knowledge (Bjork & Bjork, 2011; Kapur, 2016). Conceptual change likewise requires learners to recognize conflicts between prior beliefs and new evidence, tolerate uncertainty, and gradually reconstruct existing knowledge structures (Vosniadou, 2013).

Disciplinary literacy further illustrates why continuity matters in science. Scientific reading involves more than extracting isolated information; students must interpret technical terminology, diagrams, data displays, causal relationships, and evidentiary claims across multiple representational forms (Shanahan & Shanahan, 2008). Inferential comprehension and conceptual integration develop through continued interaction with a text, representation, or problem rather than through brief exposure alone (Alexander, 2005; Wolf & Barzillai, 2009). Scientific writing, modeling, argumentation, and laboratory analysis similarly require learners to maintain relationships among evidence, concepts, and explanations over time.

3.3. From Individual Regulation to Ecological Conditions

Executive functioning and self-regulated learning explain important learner-level processes underlying sustained academic engagement. Students use attentional control, inhibition, metacognitive monitoring, planning, and strategic adjustment to maintain progress during demanding tasks (Diamond, 2013; Pintrich, 2002; Winne & Hadwin, 1998; Zimmerman, 2002). These capacities help explain differences in students' ability to manage distractions, monitor comprehension, and persist through complexity.

However, sustained attention should not be interpreted only as an individual trait or responsibility. Learners regulate cognition within instructional environments that vary in sensory stimulation, transition frequency, task coherence, technological complexity, and opportunities for recovery.

Environmental and attentional research provides a basis for examining these contextual influences. Physical conditions such as noise, visual complexity, and classroom design may affect concentration and learning-related outcomes (Barrett et al., 2015; S. Kaplan, 1995). Research on directed attention also suggests that prolonged attentional control may benefit from opportunities for restoration (S. Kaplan & Berman, 2010). Evidence from neuroscience and memory research—derived primarily from adult, laboratory, and non-classroom settings—further indicates that reduced external stimulation and post-encoding rest may support memory stabilization and integration (Dudai et al., 2015; Raichle, 2015; Tambini & Davachi, 2013). These findings do not establish that particular restoration practices improve secondary science learning, but they provide plausible mechanisms for testing whether reduced sensory competition, reflective pauses, and uninterrupted processing time support disciplinary cognition.

These interactions may be particularly relevant during adolescence, when executive-control and self-regulatory systems are still developing (Blakemore & Choudhury, 2006; Steinberg, 2005). CELF does not assume that attentional fragmentation affects all students uniformly or that environmental conditions override learner agency. Prior knowledge, motivation, sleep, stress, developmental variation, instructional clarity, accessibility needs, and classroom climate may also influence sustained cognition.

Cognitive architecture explains the limitations and regulatory processes involved in demanding learning; science education and disciplinary literacy identify the forms of reasoning that must be sustained; self-regulated learning explains how learners monitor and direct cognition; and environmental perspectives identify contextual conditions that may support or constrain that regulation. These foundations establish sustained disciplinary cognition as an interaction between learner-level processes and classroom-level instructional and environmental conditions.

4. Fragmented Attention in Modern Learning Environments

This section reviews research on interruption, media multitasking, task switching, digital reading, workflow complexity, and environmental competition as mechanisms that may disrupt the continuity of disciplinary cognition. The synthesis establishes the evidentiary basis for the attentional-fragmentation dimension formally assembled within CELF.

4.1. Interruption, Multitasking, and Task Switching

Attentional fragmentation refers to repeated disruptions in the continuity of goal-directed cognitive processing. It may arise from notifications, competing media, environmental interruptions, workflow complexity, or rapid movement among tasks and platforms. Sustained attention requires learners to maintain task goals while filtering stimuli that are not relevant to the activity at hand (Posner & Rothbart, 2007; Sarter et al., 2001). In

technology-rich environments, several informational streams may therefore compete for limited attentional and working-memory resources.

Media-multitasking research suggests that frequent switching among information sources may be associated with weaker attentional filtering and greater susceptibility to competing stimuli, although findings vary across individuals, tasks, and research designs (Ophir et al., 2009; Uncapher & Wagner, 2018). Educational studies provide more direct evidence that task-irrelevant digital activity can interfere with learning. Laptop multitasking has been associated with reduced learning among both users and nearby peers, while nonacademic internet use during class has been linked with lower academic performance (Ravizza et al., 2017; Sana et al., 2013). These findings do not demonstrate that all simultaneous or technology-mediated activity impairs learning. They indicate that competing activity may divert cognitive resources when it is unrelated to the instructional goal.

Task-switching research helps explain why interruption may remain consequential after a learner returns to the original activity. Alternating between tasks requires executive reconfiguration and may increase response time, error, and processing inefficiency (Pashler, 1994; Rubinstein et al., 2001). Interruptions may also displace active goals, requiring learners to reconstruct what they were doing before the disruption occurred (Altmann & Trafton, 2002). Attention residue may persist when cognitive elements of an unfinished task continue to interfere after a behavioral transition (Leroy, 2009). Interruptions in digital work settings have likewise been associated with increased stress and accelerated work pace, even when observable productivity recovers (Mark et al., 2008).

4.2. Digital Reading and Fragmented Information Processing

Digital reading provides another context in which instructional design may influence attentional continuity. Deep disciplinary reading requires learners to construct inferences, integrate ideas across a text, connect verbal and visual representations, and retain conceptual relationships while their understanding develops (Alexander, 2005; Wolf & Barzillai, 2009). Some online environments may complicate these processes by requiring frequent navigation, hyperlink decisions, scrolling, or movement among informational sources (DeStefano & LeFevre, 2007; Liu, 2005).

Comparative and meta-analytic research has identified comprehension disadvantages for screen-based reading under some conditions, particularly when tasks involve informational texts, time pressure, or deeper comprehension demands (Delgado et al., 2018; Mangen et al., 2013). Wolf (2018) similarly argued that habitual digital interruption may reduce opportunities for reflective reading. These findings should not be interpreted as evidence that print is inherently superior or that digital reading necessarily produces shallow processing. Outcomes vary according to text structure, device design, learner experience, navigation requirements, instructional support, and the purpose of reading.

For CELF, the relevant distinction is not between print and digital media in isolation. It is between environments that preserve conceptual continuity and environments that repeatedly redirect attention toward navigation, peripheral information, or unrelated stimuli. This distinction is especially important in secondary science, where students may need to coordinate explanatory text, diagrams, simulations, data tables, laboratory procedures, and evidentiary claims. Movement among these representations can support learning when the elements are conceptually aligned. It becomes fragmenting when students must manage unnecessary windows, links, platforms, or competing prompts that do not advance the disciplinary task.

4.3. Cumulative Fragmentation Across the Learning Environment

The present synthesis considers whether reorientation demands accumulate beyond individual interruptions across a lesson, instructional period, or school day. Broader accounts of digital culture suggest that persistent connectivity, rapid communication, and continual informational availability may encourage shorter cycles of attentional engagement (Carr, 2010; Gazzaley & Rosen, 2016; Mark, 2023; Turkle, 2015). These works provide conceptual interpretations rather than direct causal evidence from secondary science classrooms. Their relevance lies in identifying patterns that warrant empirical investigation.

Fragmentation may also arise from nondigital conditions. Noise, visual complexity, classroom design, procedural interruptions, and frequent transitions may affect concentration and cognitive performance (Barrett et al., 2015; Evans & Johnson, 2000; S. Kaplan, 1995). Research on cognitive fatigue further suggests that prolonged demands for attentional control without sufficient recovery may reduce executive efficiency and sustained concentration (Boksem & Tops, 2008; Hockey, 2013). In secondary schools, short work intervals, rapid transitions among subjects, competing classroom stimuli, and frequent procedural changes may therefore create recurring demands for disengagement and reorientation. Direct evidence connecting these cumulative conditions to secondary science outcomes remains limited.

Taken together, this literature suggests that interruptions, task switching, competing stimulation, workflow complexity, and repeated cognitive reorientation may create cumulative pressure on disciplinary processing. The educational significance of these conditions depends on their function rather than their frequency alone. Movement among tools, representations, or phases of inquiry may support learning when it advances a coherent conceptual objective. The same movement may become fragmented when it interrupts unfinished reasoning, displaces the task goal, or requires students to reconstruct their conceptual position repeatedly.

4.4. Boundaries and Alternative Explanations

Purposeful movement among scientific representations, collaborative roles, laboratory tools, or phases of inquiry may support learning when those transitions are coordinated around a shared conceptual objective. Multimedia resources, simulations, and online inquiry environments can strengthen visualization, accessibility, collaboration, and scientific investigation when they direct attention toward relevant relationships (de Jong et al., 2013; Mayer, 2021; Means et al., 2010).

The relevant distinction is therefore between:

- Instructionally meaningful shifting, which advances or reorganizes disciplinary processing;
- Fragmenting competition, which interrupts, displaces, or unnecessarily complicates that processing.

The evidence reviewed in this section supports treating attentional fragmentation as a contextual condition that may interfere with sustained disciplinary processing, rather than as a synonym for technology use, distraction, or transition frequency.

5. Cognitive Malnourishment as a Conceptual Lens

This section defines cognitive malnourishment, explains the theoretical basis for the construct, distinguishes it from related concepts, and establishes its empirical boundaries.

5.1. Definition and Constituent Conditions

Cognitive malnourishment refers to a proposed ecological condition in which learners encounter substantial informational exposure or Disciplinary Cognitive Demand but re-

ceive insufficient opportunities for sustained elaboration, reflection, retrieval, conceptual integration, and consolidation.

The term malnourishment is used metaphorically to emphasize that abundant informational input does not necessarily produce durable conceptual understanding. Students may complete assignments, interact with multiple technologies, participate in discussion, and respond to instructional prompts while having limited opportunities to maintain and develop a coherent line of disciplinary reasoning. The construct does not imply that students are intellectually deficient, unmotivated, incapable of sustained thought, or clinically impaired. It describes conditions surrounding learning, not a category of learner.

Cognitive malnourishment is proposed to become more plausible when three conditions recur together:

1. Learners encounter substantial Disciplinary Cognitive Demand or informational exposure;
2. Attentional Fragmentation Conditions repeatedly disrupt, abbreviate, or displace attentional continuity;
3. Restoration Opportunities for elaboration, reflection, rehearsal, consolidation, or recovery remain insufficient.

No single difficult task, distraction, short lesson, or weak performance would establish cognitive malnourishment. The construct instead describes a recurring ecological imbalance across a lesson, instructional sequence, or series of learning experiences.

During a genetics investigation, students might move among an explanatory text, simulation, data table, LMS directions, collaborative document, and response form. These tools could support meaningful inquiry when organized around one coherent explanatory problem. However, if repeated platform changes, procedural interruptions, and compressed response periods leave little opportunity to connect genotype, phenotype, probability, and evidence, students may complete every required step without developing an integrated explanation.

5.2. Distinction from Related Constructs

Cognitive malnourishment overlaps with several established concepts but is not intended to replace them. Cognitive overload occurs when the demands of a task exceed the learner's available cognitive resources (Sweller, 1988; Sweller et al., 2011). It generally concerns the relationship between cognitive capacity and immediate processing demands. Cognitive malnourishment may occur without acute overload when individual activities remain manageable but are consistently fragmented, abbreviated, or insufficiently connected to opportunities for deeper processing.

Distraction refers to the diversion of attention away from a target activity (Posner & Rothbart, 2007; Sarter et al., 2001). A distraction may contribute to cognitive malnourishment, but a single attentional diversion does not establish the broader ecological condition. Cognitive malnourishment concerns recurring conditions that limit students' opportunities to resume, elaborate, and consolidate disciplinary reasoning.

Attentional fatigue refers to a reduced capacity to sustain directed control following prolonged cognitive effort (Boksem & Tops, 2008; S. Kaplan & Berman, 2010). Fatigue may be one consequence of extended regulatory demand, whereas cognitive malnourishment describes the broader instructional mismatch within which fatigue, interruption, and insufficient recovery may occur.

Shallow processing describes the level or quality at which information is encoded (Craik & Lockhart, 1972; Craik & Tulving, 1975). Cognitive malnourishment is not itself a level of processing. It concerns environmental and instructional conditions that may

repeatedly favor abbreviated or discontinuous processing over elaboration, integration, and retrieval.

The construct also differs from behavioral disengagement and low cognitive engagement. Engagement is multidimensional, and observable participation does not necessarily demonstrate sustained investment in understanding (Fredricks et al., 2004; Sinatra et al., 2015). A student may comply with directions, use the required technology, participate in group work, and submit an assignment while receiving limited opportunities to construct conceptual depth. Conversely, a student who pauses, rereads, or temporarily withdraws from discussion may still be engaged in substantial cognitive processing.

The proposed contribution of cognitive malnourishment lies in its emphasis on ecological insufficiency across time, specifically the recurring absence of conditions needed to transform informational exposure into integrated disciplinary understanding.

5.3. Theoretical Basis and Proposed Mechanisms

The theoretical basis for cognitive malnourishment begins with research on depth of processing. Information is more likely to be retained and integrated when learners engage in meaningful elaboration rather than superficial exposure (Craik & Lockhart, 1972; Craik & Tulving, 1975). Memory consolidation further involves processes through which recently encoded information becomes stabilized and reorganized over time (Dudai et al., 2015).

Research on limited attention and informational abundance provides an additional foundation. Learners must select among competing inputs because attention and working memory cannot process all available information simultaneously (Bawden & Robinson, 2009; Eppler & Mengis, 2004; Miller, 1956; Simon, 1971).

Research on expertise also informs the construct. Experts organize information into interconnected knowledge structures that support efficient interpretation and retrieval (Chi et al., 1981; Ericsson & Kintsch, 1995). Secondary science students, as disciplinary novices, require repeated opportunities to connect evidence with explanations, coordinate representations, revisit concepts, and revise models. These structures are unlikely to develop through exposure to disconnected information alone. Learning environments that consistently prioritize coverage, speed, and task completion may therefore provide fewer opportunities for students to organize knowledge into coherent disciplinary structures.

Ecological and social-cognitive perspectives further support examining these processes as interactions between learners and environments. Learning and behavior emerge through reciprocal relationships among individual characteristics, activities, social conditions, and environmental structures (Bandura, 1986; Bronfenbrenner, 1979). Applied to CELF, students exercise attentional control within settings that vary in workflow coherence, sensory stimulation, transition frequency, instructional pacing, technological complexity, and opportunities for reflection. This framing does not remove learner agency; it prevents weak conceptual persistence from being attributed exclusively to motivation, discipline, or effort.

Attentional-fatigue and restoration research provides a possible mechanism connecting these conditions. Sustained attention requires continued regulation, and lapses may reflect changes in cognitive control and resource allocation (Thomson et al., 2015). Directed attention may also benefit from opportunities for recovery following prolonged demand (S. Kaplan & Berman, 2010).

The proposed relationship can be summarized as follows:

- Disciplinary Cognitive Demand requires students to sustain complex disciplinary processing.
- Attentional Fragmentation Conditions may repeatedly interrupt or displace that processing.

- Insufficient Restoration Opportunities may constrain attentional recovery, reflection, and consolidation.
- Cognitive malnourishment may emerge when these conditions remain persistently imbalanced.

5.4. Empirical Boundaries and Alternative Explanations

Because cognitive malnourishment has not been empirically validated, it should be treated as a hypothesis-generating construct rather than a directly observable state. No single behavior, survey response, cognitive score, or learning outcome would be sufficient to demonstrate its presence. Empirical investigation would require converging evidence across instructional and environmental conditions, learning processes, and disciplinary outcomes.

Potential contextual evidence might include recurring interruption, platform switching, abbreviated work intervals, competing sensory stimulation, and limited uninterrupted processing or reflection. Process evidence might include repeated difficulty resuming reasoning, weak elaboration, abbreviated explanations, limited integration among representations, or reduced continuity during extended inquiry. Outcome evidence could include delayed retention, transfer, conceptual integration, and the quality of evidence-based explanations.

Alternative explanations must remain central to interpretation. Weak conceptual integration may reflect limited prior knowledge, inappropriate task difficulty, insufficient scaffolding, low motivation, sleep loss, stress, language demands, accessibility barriers, classroom climate, instructional clarity, or developmental differences. Some rapid navigation, multimodal coordination, and collaborative digital activity may also strengthen learning when organized around a coherent disciplinary purpose.

Human cognition remains adaptive and responsive to experience and environmental conditions (Lövdén et al., 2010). CELF does not propose that contemporary students have lost the capacity for prolonged thought. Rather, it proposes that learning environments differ in how consistently they provide opportunities to exercise sustained disciplinary cognition.

6. Cognitive Endurance in Secondary Science Classrooms

This section defines cognitive endurance, distinguishes it from adjacent constructs, and considers the instructional conditions under which sustained disciplinary cognition may be supported.

6.1. Definition and Conceptual Boundaries

Cognitive endurance refers to the context-sensitive capacity to sustain attention, conceptual processing, disciplinary reasoning, and reflective engagement across an extended, cognitively demanding task. It involves maintaining a coherent line of reasoning while coordinating evidence, concepts, and representations; monitoring understanding; and recovering from temporary lapses or difficulty.

Cognitive endurance should not be inferred solely from time on task, behavioral compliance, task completion, or visible persistence. A student may remain seated and continue working without meaningfully interpreting evidence or revising understanding. Conversely, a student who pauses, rereads, reflects, or temporarily reduces outward participation may remain cognitively engaged. The construct therefore concerns the continuity and quality of disciplinary processing rather than uninterrupted observable activity.

Cognitive endurance overlaps with several established constructs but is not synonymous with them. Sustained attention refers primarily to maintaining goal-directed focus

over time, whereas cognitive endurance additionally involves the continued coordination of disciplinary content, evidence, representations, and reasoning processes (Sarter et al., 2001). Executive control supports inhibition, goal maintenance, attentional selection, and task regulation, but it describes cognitive mechanisms rather than the broader educational capacity proposed (Diamond, 2013). Self-regulated learning involves planning, monitoring, strategy selection, and adaptation; these processes may support cognitive endurance but do not independently demonstrate that prolonged disciplinary reasoning has occurred (Pintrich, 2002; Winne & Hadwin, 1998; Zimmerman, 2002).

Cognitive endurance also differs from persistence and grit. Persistence indicates continued effort, while grit generally concerns perseverance toward long-term goals (Duckworth, 2016). Students may persist mechanically, repeat ineffective strategies, or continue a task without integrating evidence or deepening understanding. Cognitive endurance is narrower and more situational: it concerns whether learners can remain cognitively engaged with a particular disciplinary problem under instructional and environmental conditions. Instructional conditions may support or constrain students' ability to sustain reasoning. Cognitive endurance is consequently neither a stable personality characteristic nor a judgment about student effort.

6.2. Sustained Disciplinary Processing

Cognitive endurance becomes educationally meaningful when students can sustain the disciplinary processes through which understanding is constructed, integrated, and revised over time. Reading comprehension develops through the gradual construction and integration of ideas across a text rather than through exposure to isolated information (Kintsch, 1998). Disciplinary reading similarly requires students to construct inferences, interpret representations, and connect new information with prior knowledge (Guthrie & Wigfield, 2000; Wolf & Barzillai, 2009).

Inquiry, argumentation, modeling, and evidence evaluation may also require prolonged engagement. Students must often formulate an initial explanation, compare it with evidence, recognize inconsistencies, and revise their reasoning. Inquiry supports these processes when it is appropriately scaffolded and organized around a coherent disciplinary problem rather than presented as minimally guided activity (Bransford et al., 2000; Hmelo-Silver et al., 2007). Evidence concerning problem-based learning suggests potential benefits for skill development and longer-term retention under some conditions, although outcomes vary according to task design, guidance, and assessment (Strobel & van Barneveld, 2009).

Disciplinary literacy and generative-learning practices may further support sustained processing. Scientific annotation, explanation, argumentation, modeling, and writing-to-learn require students to reorganize information according to disciplinary purposes rather than reproduce it passively (Bangert-Drowns et al., 2004; Fiorella & Mayer, 2015; Graham & Perin, 2007; Moje, 2008). Their value does not derive merely from increasing task duration. They are relevant to cognitive endurance when they require students to maintain, elaborate, and revise a coherent conceptual relationship over time.

For example, students investigating antibiotic resistance could read a concise explanatory text, annotate relationships among variation, selection pressure, survival, and reproduction, and then interpret changes in a bacterial-population data set. Students could construct an evidence-based explanation, compare it with a competing interpretation, and revise their claim. Directions, readings, data, and response spaces could be organized within one coherent sequence. The instructional purpose would not be to keep students continuously occupied, but to preserve one conceptual thread across reading, interpretation, explanation, critique, and revision.

This example illustrates an important CELF distinction: extended work is not automatically sustained cognition. A long assignment composed of disconnected steps, repeated procedural interruptions, or passive completion may require time without supporting cognitive endurance. The construct is most relevant when task duration is paired with conceptual coherence, appropriate challenge, and meaningful opportunities to elaborate understanding.

6.3. Workflow Coherence and Instructional Pacing

Cognitive endurance may also be affected by the organization of the workflow surrounding that demand. Academic multitasking has been associated with weaker performance in some contexts, although relationships vary among learners and tasks (Junco & Cotten, 2012). The relevant implication is not that digital tools should be removed, but that unnecessary reorientation should be minimized.

A coherent digital workflow might place instructions, readings, evidence, simulations, and response prompts within an ordered sequence rather than distributing them across several unrelated applications. Notifications and peripheral prompts can be limited during sustained reasoning, while transitions can occur at meaningful conceptual points rather than at arbitrary intervals. A virtual laboratory, for instance, may support cognitive endurance when students use it to test a prediction, record evidence, and revise a model. The same activity may become fragmented when students must repeatedly search for missing directions, alternate among unrelated tabs, or reconstruct the purpose of the investigation after procedural interruptions.

Instructional pacing should similarly distinguish productive cognitive challenge from unnecessary urgency. Learning often requires retrieval, feedback, practice, and repeated engagement with important ideas (Ambrose et al., 2010). Distributed practice can support long-term retention, while retrieval practice requires learners to reconstruct knowledge rather than merely reencounter it (Cepeda et al., 2006; Karpicke & Roediger, 2008). These findings do not imply that all instruction should proceed slowly or that students should remain on one task for an arbitrarily long period. They suggest that pacing should provide sufficient time for the type of reasoning the task requires and should allow central concepts to be revisited across learning experiences.

An ecosystem-data investigation provides another illustration. Students could first receive an uninterrupted period to identify patterns and develop an initial causal explanation. A short reflective interval could then allow them to identify uncertainty or missing evidence. Small groups could compare interpretations, challenge competing explanations, and revise their claims. The relevant CELF principle is not a prescribed number of minutes but the deliberate sequence of sustained analysis, reflection, dialogue, and revision.

6.4. Restoration, Collaboration, and Metacognitive Regulation

Attention Restoration Theory suggests that prolonged directed attention may benefit from experiences that reduce regulatory demand (R. Kaplan & Kaplan, 1989). Vigilance research also indicates that rest and interruption can affect sustained-attention performance, although not all interruptions are restorative and much of this evidence comes from adult laboratory settings (Helton & Russell, 2015).

A restorative interval should not be equated with abandoning rigor or introducing unrelated entertainment. It may involve quiet reflection, reduced sensory stimulation, movement between phases of an investigation, or individual processing before discussion. To remain consistent with CELF, the interval should preserve the conceptual thread and support reengagement rather than introduce additional competition.

Collaboration may support cognitive endurance when students remain jointly responsible for disciplinary reasoning. Exploratory dialogue can promote conceptual development when learners explain, challenge, compare, and refine ideas (Mercer & Littleton, 2007). The Interactive, Constructive, Active, and Passive (ICAP) framework similarly proposes that constructive and interactive engagement can support deeper processing when learners generate and negotiate meaning (Chi & Wylie, 2014). Collaborative activity is therefore most consistent with cognitive endurance when students analyze shared evidence, defend explanations, identify contradictions, and revise collective claims.

Collaboration does not automatically support sustained cognition. Dividing a complex problem into isolated roles may allow students to complete assigned components without understanding the full disciplinary relationship. Group work may also become fragmented when attention is distributed among procedural management, unrelated conversation, and disconnected contributions. The relevant criterion is whether collaboration sustains shared attention to the conceptual problem.

Metacognitive regulation may help learners maintain and recover disciplinary reasoning. Self-explanation prompts can support understanding by encouraging students to connect new information with prior knowledge and make their reasoning explicit (Chi et al., 1994). Students might explain which evidence changed their interpretation, identify where their reasoning became uncertain, describe what interrupted their thought process, or determine which part of the explanation requires revision. Such prompts can make sustained cognition more observable without treating a single response as a direct measure of cognitive endurance.

Digital tools may facilitate these processes when they serve a clear disciplinary function. Computer-guided inquiry environments can organize evidence, prompts, and feedback around coherent scientific goals (Linn et al., 2014). CELF therefore does not privilege print over digital instruction, individual work over collaboration, or uninterrupted work over all transitions. It asks whether the selected tools, participation structures, pacing, and recovery opportunities support or compete with the reasoning required by the disciplinary task.

7. The Cognitive Ecology of Learning Framework

The Cognitive Ecology of Learning Framework (CELF) is proposed as an applied organizing framework for examining the conditions under which students can sustain disciplinary cognition in technology-rich secondary science classrooms. It organizes selected cognitive, attentional, disciplinary, and environmental constructs around three classroom-level dimensions: Disciplinary Cognitive Demand, Attentional Fragmentation Conditions, and Restoration Opportunities. These dimensions may interact across extended instructional experiences. Figure 1 summarizes the theoretical derivation of CELF. It distinguishes the established perspectives informing the framework from CELF's proposed classroom-level organization of selected constructs and mechanisms.

Figure 2 presents the framework's proposed internal architecture. Disciplinary Cognitive Demand, Attentional Fragmentation Conditions, and Restoration Opportunities are represented as analytically distinct but interacting classroom-level dimensions surrounding sustained disciplinary cognition. Cognitive malnourishment and cognitive endurance are positioned as proposed emergent constructs associated with interactions among these dimensions rather than as predetermined learner outcomes.

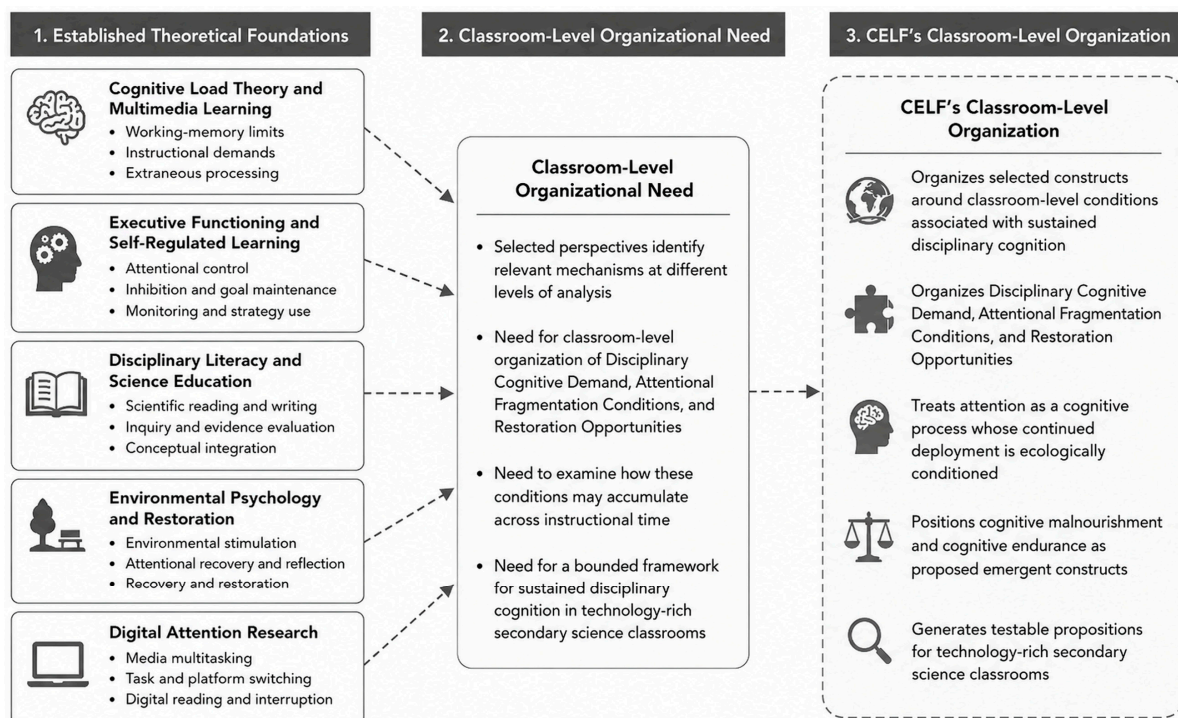


Figure 1. Theoretical foundations and conceptual derivation of the Cognitive Ecology of Learning Framework. Solid borders indicate established theoretical perspectives. Dashed borders indicate CELF's proposed classroom-level dimensions and emergent constructs requiring empirical validation. Arrows represent the proposed organization of selected constructs and mechanisms rather than causal or temporal relationships.

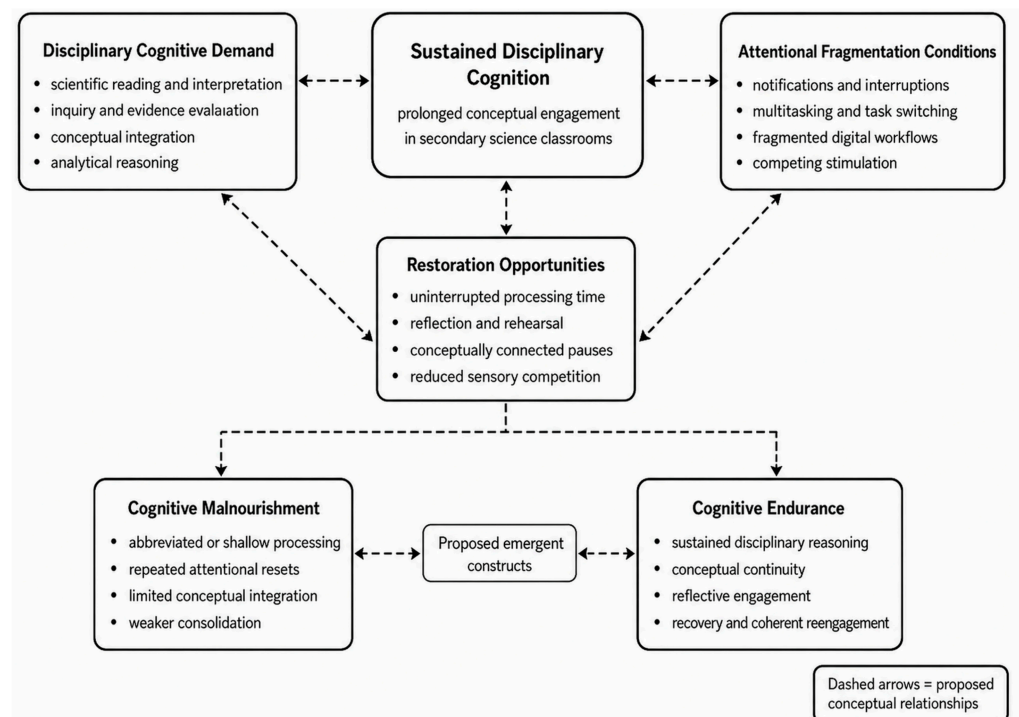


Figure 2. Proposed internal architecture of the Cognitive Ecology of Learning Framework. Dashed arrows indicate proposed conceptual relationships requiring empirical testing rather than established causal or temporal pathways. The figure foregrounds CELF's classroom-level dimensions and does not represent every learner-level, instructional, or contextual influence on sustained disciplinary cognition.

7.1. Theoretical Derivation and Scope of CELF

CELF is presented as an applied, mid-range organizing framework for technology-rich secondary science classrooms. It does not test, revise, or replace the foundational propositions of Cognitive Load Theory, Self-Regulated Learning, multimedia learning, executive-functioning research, or environmental psychology. Instead, it draws on selected constructs from these traditions—including working-memory constraints, unnecessary processing, metacognitive monitoring, attentional reorientation, environmental restoration, and disciplinary literacy—to organize a classroom-level question: how may Disciplinary Cognitive Demand, Attentional Fragmentation Conditions, and Restoration Opportunities interact in relation to sustained disciplinary cognition? CELF's contribution is therefore contextual and organizational rather than foundational. It specifies proposed relationships among selected mechanisms within a bounded instructional environment and generates propositions for classroom-based empirical testing.

To clarify this theoretical derivation without positioning CELF as a competitor to established theories, Table 2 identifies the specific constructs drawn from the contributing literature, their established functions, their roles within CELF, and the boundaries of the claims advanced here. The comparison therefore occurs at the level of selected mechanisms and classroom applications rather than between CELF and complete theoretical systems.

Table 2. Theoretical Constructs Informing the Development of the Cognitive Ecology of Learning Framework.

Contributing Construct and Source	Established Function or Unit of Analysis	Role Within CELF	Boundary of CELF's Claim
Working-memory constraints and unnecessary processing (Sweller, 1988; Sweller et al., 2011)	Explains the relationship between instructional demands, limited working-memory capacity, and processing that does not directly support learning.	Informs Disciplinary Cognitive Demand and the distinction between productive disciplinary challenge and avoidable cognitive competition surrounding a task.	CELF does not revise Cognitive Load Theory, propose a new category of cognitive load, or alter its established working-memory principles.
Multimedia processing and instructional design (Mayer, 2021)	Examines how verbal and visual information should be organized to direct limited processing resources toward relevant conceptual relationships.	Informs analysis of whether digital materials and workflows support coherent processing or introduce unnecessary attentional competition.	CELF does not replace multimedia-learning principles or claim that digital instruction is inherently fragmenting.
Metacognitive monitoring and strategic regulation (Pintrich, 2002; Winne & Hadwin, 1998; Zimmerman, 2002)	Addresses learners' planning, monitoring, strategy selection, adaptation, and regulation of cognition and behavior during learning.	Informs how learners maintain, recover, and redirect disciplinary reasoning under demanding or interrupted conditions.	CELF does not revise models of self-regulated learning or treat cognitive endurance as synonymous with metacognitive regulation or strategy use.
Executive control and attentional regulation (Diamond, 2013; Engle, 2002; Posner & Rothbart, 2007)	Identifies mechanisms supporting inhibition, goal maintenance, attentional selection, and control of task-relevant cognition.	Informs the mechanisms through which learners filter competing stimuli and preserve a disciplinary goal across time.	CELF does not propose a new model of executive functioning or make neuroscientific claims about underlying mechanisms.
Digital interruption, task switching, and attentional reorientation (Mark et al., 2008; Ophir et al., 2009; Rosen et al., 2011; Uncapher & Wagner, 2018)	Examines interference, attentional residue, filtering difficulty, and the costs associated with repeated switching and interruption.	Informs Attentional Fragmentation Conditions as a classroom-level dimension encompassing interruptions, competing stimulation, workflow complexity, and reorientation that disrupt or displace disciplinary reasoning.	CELF does not assume that all transitions, device use, or multimodal activity are detrimental.

Table 2. *Cont.*

Contributing Construct and Source	Established Function or Unit of Analysis	Role Within CELF	Boundary of CELF's Claim
Environmental demand, attention restoration, and cognitive recovery (S. Kaplan, 1995; S. Kaplan & Berman, 2010; R. Kaplan & Kaplan, 1989)	Examines how sensory conditions, directed-attention fatigue, reduced stimulation, and opportunities for recovery influence cognition.	Informs Restoration Opportunities as instructional and environmental provisions for attentional recovery, reflection, consolidation, and coherent reengagement.	CELF does not claim that classroom pauses are automatically restorative or that restoration substitutes for rigorous learning.
Disciplinary literacy, inquiry, and science reasoning (Duschl, 2008; Moje, 2008; National Research Council, 2012; Osborne, 2010; Shanahan & Shanahan, 2008)	Defines the specialized reading, writing, modeling, evidence evaluation, explanation, and argumentation practices required in science.	Specifies the forms of disciplinary cognition that students must sustain and the context in which CELF is intended to operate.	CELF does not offer a general theory of disciplinary learning and is bounded primarily to technology-rich secondary science classrooms.

Note. The contributing constructs are presented at the level of selected mechanisms and classroom applications rather than as complete theoretical systems. CELF draws on these constructs to organize a bounded classroom-level framework; it does not revise, replace, or directly test the foundational theories from which they are derived.

These contributing constructs inform CELF as an applied, hypothesis-generating framework for examining sustained cognition in technology-rich secondary science classrooms. The framework organizes task-level demand, learner regulation, disciplinary practice, attentional fragmentation, and restoration opportunities within a cumulative classroom-level ecological frame without revising or replacing the theories from which these constructs are drawn.

7.2. Core Dimensions of CELF

CELF contains three interacting dimensions: Disciplinary Cognitive Demand, Attentional Fragmentation Conditions, and Restoration Opportunities. These dimensions are analytically distinguishable but are not assumed to operate independently.

7.2.1. Disciplinary Cognitive Demand

Disciplinary Cognitive Demand refers to the intellectual requirements inherent in sustained secondary science learning, including interpreting evidence, coordinating representations, constructing explanations, revising models, reading disciplinary texts, and reasoning through conceptual uncertainty. These demands may be productive and necessary rather than inherently detrimental. The relevant question is not whether a task is difficult, but whether the surrounding instructional conditions allow students to remain engaged with its disciplinary demands long enough for elaboration, revision, and conceptual integration to occur.

7.2.2. Attentional Fragmentation Conditions

Attentional Fragmentation Conditions refers to interruptions, task switching, competing stimulation, workflow complexity, and repeated cognitive reorientation that disrupt or displace an active line of disciplinary reasoning. The construct concerns the function of attentional shifting rather than the number of devices, tools, or transitions present. Purposeful movement among aligned representations does not constitute fragmentation when it advances the conceptual objective. Fragmentation occurs when switching obscures that objective, interrupts unfinished processing, or requires learners repeatedly to reconstruct their reasoning.

7.2.3. Restoration Opportunities

Restoration Opportunities refer to instructional and environmental conditions that support attentional recovery, reflection, consolidation, and coherent reengagement with disciplinary work. Such opportunities may include quiet processing, reflective writing, reduced sensory competition, conceptually connected pauses, or temporary reductions in reorientation demands. Time alone is not restorative; an interval functions as restoration only when it helps learners recover or preserve the conceptual thread required for subsequent reasoning.

7.3. Emergent Constructs: Cognitive Malnourishment and Cognitive Endurance

Cognitive malnourishment and cognitive endurance are proposed as emergent, context-sensitive constructs rather than fixed learner traits or directly observable states. They are positioned as possible patterns associated with the interactions among Disciplinary Cognitive Demand, Attentional Fragmentation Conditions, Restoration Opportunities, learner characteristics, and instructional context. The framework does not assume that either construct follows automatically from any single dimension.

Cognitive malnourishment may become more plausible when substantial disciplinary or informational demand coincides with persistent fragmentation and insufficient opportunities for elaboration, reflection, consolidation, and coherent reengagement. This proposition concerns an ecological mismatch across learning experiences, not a diagnosis of the learner and not an inevitable effect of technology use. The construct would require converging evidence across instructional conditions, learning processes, and disciplinary outcomes.

Cognitive endurance may be supported when demanding disciplinary work occurs under conditions that preserve conceptual continuity, provide appropriate scaffolding, and allow learners to recover from interruption or cognitive effort without losing the central reasoning problem. CELF therefore treats endurance as context-sensitive and potentially developmental: it may be strengthened through repeated opportunities for sustained inquiry, disciplinary reading, evidence evaluation, explanation, and revision. These proposed relationships remain hypotheses requiring classroom-based empirical testing.

7.4. Framework Propositions

CELF is organized around five propositions that translate the framework's conceptual relationships into hypotheses for future empirical investigation.

1. Sustained Fragmentation proposition. When Disciplinary Cognitive Demand is held relatively constant, more persistent Attentional Fragmentation Conditions are expected to be associated with more frequent cognitive reorientation, weaker conceptual continuity, and lower performance during extended disciplinary-reasoning tasks.
2. Ecological-imbalance proposition. Cognitive malnourishment is expected to become more plausible when substantial Disciplinary Cognitive Demand or informational exposure coincides with persistent Attentional Fragmentation Conditions and insufficient Restoration Opportunities for elaboration, consolidation, and recovery.
3. Restoration proposition. Restoration Opportunities are expected to moderate the relationship between Disciplinary Cognitive Demand and learning outcomes, such that demanding tasks may support stronger conceptual learning when learners have sufficient opportunities for reflection, rehearsal, recovery, and coherent reengagement.
4. Workflow-coherence proposition. Technology-rich instruction is expected to support sustained disciplinary cognition more effectively when digital workflows reduce unnecessary reorientation and preserve conceptual continuity than when they introduce competing attentional demands.

5. Endurance-development proposition. Repeated engagement in sustained disciplinary reading, inquiry, evidence evaluation, explanation, and revision under supportive instructional conditions is expected to be associated with the development of cognitive endurance over time.

These propositions establish a preliminary empirical agenda rather than a fixed instructional model.

7.5. Operationalizing CELF for Future Research

Disciplinary Cognitive Demand, Attentional Fragmentation Conditions, and Restoration Opportunities should be examined through converging evidence rather than inferred from a single behavior, score, or classroom feature. Cognitive malnourishment and cognitive endurance should likewise be treated as emergent patterns requiring evidence across instructional conditions, learner experiences, and disciplinary outcomes.

Future studies may combine task analysis, classroom observation, student reports, digital trace data, experience sampling, task-resumption measures, written-response analysis, delayed-retention assessments, and transfer tasks. For example, platform switching would indicate Attentional Fragmentation Conditions only when the switching disrupts rather than advances the conceptual objective. Similarly, uninterrupted work time would constitute evidence of Restoration Opportunities only when it supports reflection, recovery, or coherent reengagement rather than prolonged confusion or disengagement.

Table 3 presents preliminary definitions, indicators, measurement approaches, and alternative explanations. These elements are intended to guide construct development and pilot testing rather than function as a validated CELF instrument.

Table 3. Preliminary operationalization of CELF dimensions and emergent constructs.

CELF Construct	Conceptual Definition	Possible Indicators	Potential Measurement Approaches	Important Alternative Explanations
Disciplinary Cognitive Demand	Intellectual demands associated with sustained disciplinary learning.	Task complexity; number of representations coordinated; abstract reasoning; evidence evaluation; problem solving; conceptual integration.	Task analysis; adapted task-demand and cognitive-load ratings; think-aloud protocols; teacher ratings; student self-report; performance-task analysis.	Prior knowledge; task familiarity; reading proficiency; instructional clarity.
Attentional Fragmentation Conditions	Instructional and environmental conditions involving interruption, switching, competing stimulation, workflow complexity, and repeated cognitive reorientation that disrupt or displace disciplinary reasoning.	Notifications; task or platform switching; interruption frequency; noise; visual competition; task-irrelevant digital activity; frequency and timing of attentional reorientation; task-resumption time.	Classroom observation; interruption logs; LMS clickstream data; device-use records; ecological momentary assessment; resumption-lag measures.	Intentional instructional transitions; learner preference; technological fluency; task design.
Restoration Opportunities	Opportunities within the instructional environment for attentional recovery, reflection, consolidation, and coherent reengagement.	Uninterrupted processing time; reflective intervals; reduced sensory competition; coherent transitions; independent synthesis; opportunities for rehearsal; conceptually connected pauses.	Schedule and lesson-plan analysis; observation protocols; student experience reports; environmental ratings; duration and quality of reflective intervals.	Boredom; disengagement; excessive task duration; unrelated breaks; fatigue.

Table 3. Cont.

CELF Construct	Conceptual Definition	Possible Indicators	Potential Measurement Approaches	Important Alternative Explanations
Cognitive malnourishment	Proposed ecological mismatch in which substantial informational exposure or Disciplinary Cognitive Demand coincides with persistent Attentional Fragmentation Conditions and insufficient Restoration Opportunities for sustained conceptual processing.	Frequent attentional resets; shallow explanations; limited conceptual integration; weak delayed retention; difficulty coherently resuming disciplinary reasoning despite visible activity.	Student interviews; written-response analysis; delayed-retention tasks; think-aloud protocols; observation; longitudinal case studies; convergent profile analysis.	Motivation; prior knowledge; sleep; stress; language proficiency; task difficulty; instructional quality.
Cognitive endurance	Context-sensitive capacity to sustain attention and disciplinary reasoning during extended cognitively demanding work.	Sustained inquiry; explanatory depth; continued conceptual engagement through ambiguity; coherent recovery after interruption; continuity of evidence-based reasoning across task phases.	Extended performance tasks; inquiry-duration metrics; observation; written explanations; delayed-transfer tasks; growth modeling; student self-report.	Grit; sustained attention; self-regulation; executive functioning; motivation; content expertise.

Note. The indicators and measurement approaches are preliminary and should not be interpreted as validated measures of CELF constructs. Existing instruments may provide relevant component measures, but construct evaluation would require converging evidence across instructional conditions, learner processes, and disciplinary outcomes.

7.6. Instructional Design Applications

CELF's propositions may also inform provisional instructional-design questions. These applications are not validated interventions or prescriptive requirements. They simply illustrate how educators might examine whether task structure, workflow, pacing, technology use, and reflection support or compete with sustained disciplinary reasoning. Table 4 connects common CELF concerns with possible design responses, secondary science examples, and intended cognitive functions.

Table 4. Illustrative CELF-informed instructional design applications.

CELF Concern	Design Response	Secondary Science Classroom Example	Intended Cognitive Function
High Disciplinary Cognitive Demand	Scaffold complex reasoning without reducing disciplinary rigor.	Sequence laboratory analysis through evidence identification, claim construction, and explanatory revision.	Supports coordination of evidence and concepts while preserving productive challenge.
Persistent Attentional Fragmentation Conditions	Reduce unnecessary switching and consolidate instructional workflow.	Place directions, readings, data tables, simulation links, and submission materials within one ordered LMS sequence.	Preserves conceptual continuity and reduces repeated cognitive reorientation.
Limited Restoration Opportunities	Include conceptually connected opportunities for reflection and recovery.	Provide a brief quiet written synthesis after data analysis before students begin group discussion.	Supports consolidation, attentional recovery, and coherent reengagement.

Table 4. Cont.

CELf Concern	Design Response	Secondary Science Classroom Example	Intended Cognitive Function
Risk of cognitive malnourishment	Increase the duration and depth of conceptual processing.	Ask students to annotate, discuss, and explain one complex scientific text rather than rotate rapidly among several brief digital activities.	Promotes elaboration, inferential reasoning, and conceptual integration.
Development of cognitive endurance	Increase the duration and complexity of disciplinary reasoning gradually.	Progress from short evidence-based responses to extended scientific arguments requiring revision after peer critique.	Provides repeated practice sustaining reasoning through complexity and ambiguity.
Fragmented collaborative work	Structure collaboration around shared reasoning rather than disconnected roles.	Have groups interpret the same data set, compare competing explanations, and revise a collective claim.	Maintains joint attention to a coherent disciplinary problem.
Unfocused technology use	Align each digital tool with a clearly defined disciplinary purpose.	Use a simulation to test a prediction and revise a model rather than requiring students to alternate among unrelated applications.	Directs technology toward conceptual reasoning rather than peripheral activity.

Note. Examples presented should be adapted to learners' developmental levels, prior knowledge, accessibility needs, disciplinary content, and classroom conditions.

7.7. Implications for Secondary Science Education

CELf raises questions about how school systems organize the conditions surrounding sustained science learning. Scheduling structures, learning-management-system architecture, platform adoption, assessment calendars, and device policies may shape how often students must interrupt, resume, or reorganize complex disciplinary reasoning. These structures should therefore be evaluated not only for administrative efficiency and technological access, but also for their implications for instructional continuity, cognitive reorientation, and opportunities for conceptual consolidation.

CELf also has implications for curriculum planning, technology procurement, and professional learning. Schools could consider whether required digital systems create coherent pathways among scientific texts, data, simulations, laboratory procedures, and student responses or distribute these elements across unnecessarily complex workflows. Technology decisions should account for accessibility, disciplinary purpose, teacher autonomy, and the cognitive demands imposed by implementation. Professional learning may similarly help educators distinguish productive movement among scientific representations from procedural switching that does not advance the conceptual objective.

At the policy level, CELf provides a framework for examining whether institutional expectations inadvertently prioritize coverage, speed, and visible activity over sustained inquiry and explanation. It does not prescribe a particular schedule, device restriction, or instructional platform. Instead, it suggests that educational structures should be studied according to whether they provide students with recurring opportunities to interpret evidence, maintain conceptual relationships, revise explanations, and return coherently to demanding work. Its systems-level relevance is therefore to identify attentional continuity and sustained disciplinary cognition as considerations in decisions that are often treated as primarily logistical or technological.

8. Limitations, Boundary Conditions, and Future Research

This section defines the evidentiary, conceptual, and contextual boundaries of CELF and identifies priorities for empirical evaluation. The framework's scientific value will depend on whether its dimensions and emergent constructs can be measured reliably, distinguished from established concepts, and shown to explain meaningful variation in sustained disciplinary learning.

8.1. Evidentiary and Contextual Boundaries

CELF's evidentiary base is interdisciplinary but uneven in its proximity to the framework's target context. The literature identifies plausible mechanisms involving interruption, reorientation, fatigue, restoration, and consolidation, but it does not establish that CELF's proposed relationships operate in the same way among adolescents in secondary science classrooms. Direct classroom research examining Disciplinary Cognitive Demand, Attentional Fragmentation Conditions, and Restoration Opportunities together therefore remains necessary.

Its applicability to other age groups, disciplines, or brief and highly procedural tasks should not be assumed without empirical testing. As established earlier, purposeful movement among aligned representations, tools, and stages of inquiry does not constitute fragmentation; CELF concerns attentional shifts that disrupt or displace the conceptual continuity of disciplinary work. Its narrower purpose is to organize research on the cumulative instructional conditions surrounding sustained disciplinary cognition.

8.2. Construct Limitations and Alternative Explanations

CELF's constructs require empirical validation before they can be treated as distinct or measurable components of learning. Future research must establish whether cognitive malnourishment and cognitive endurance demonstrate reliability, discriminant validity, and incremental explanatory value when examined alongside established constructs such as cognitive load, sustained attention, self-regulation, engagement, fatigue, and persistence. Neither construct should be inferred from a single behavior, outcome, or instructional episode.

The boundaries among Disciplinary Cognitive Demand, Attentional Fragmentation Conditions, and Restoration Opportunities may also overlap in practice. The same digital workflow may increase both disciplinary demand and reorientation, while an instructional pause may function as restorative for one learner but disruptive for another. Validation should therefore examine construct overlap, learner variability, and sensitivity to task and context.

Observed outcomes may also reflect factors outside CELF, including prior knowledge, instructional quality, task difficulty, motivation, language proficiency, sleep, stress, accessibility, classroom relationships, and assessment alignment. The framework proposes probabilistic rather than deterministic relationships and should be tested alongside these alternative explanations.

CELF's applicability to students with attentional, executive-functioning, or sensory differences also remains uncertain. Research involving neurodiverse learners should avoid deficit-based interpretations and examine how instructional environments may create different demands and supports across learners.

8.3. Priorities for Empirical Testing

Empirical evaluation of CELF should begin with construct validation. Research must determine whether its three classroom-level dimensions and two emergent constructs can be measured reliably, distinguished from established concepts, and represented through

converging environmental, process, and outcome evidence. The provisional indicators and measurement approaches summarized in Table 3 provide a starting point for this work but do not constitute a validated instrument.

Subsequent experimental and quasi-experimental studies should test the framework's proposed relationships while holding disciplinary content and instructional support as constant as possible. Researchers could compare coherent and fragmented digital workflows or vary the presence of conceptually connected reflective intervals. Relevant outcomes might include task-resumption time, continuity of reasoning, explanation quality, delayed retention, transfer, and perceived interference.

Longitudinal studies are needed to examine whether cognitive endurance changes through repeated engagement in sustained disciplinary work and whether any growth transfers across tasks or contexts. Mixed-method classroom research using observations, interviews, experience sampling, digital trace data, and student work could further clarify how attentional fragmentation conditions, restoration opportunities, and sustained reasoning operate in authentic instructional settings.

Research should eventually test CELF across science disciplines, grade levels, schedules, instructional formats, and student populations. Such comparisons would help determine the conditions under which the framework is most applicable and whether its proposed relationships generalize beyond secondary science classrooms or tasks.

8.4. Comparative and Falsifiable Evaluation

Future research should evaluate CELF alongside complementary and alternative explanations rather than treating the framework as self-confirming. Studies should determine whether CELF's dimensions and emergent constructs account for variation in sustained disciplinary reasoning, conceptual integration, retention, or transfer after accounting for cognitive load, prior knowledge, motivation, self-regulation, instructional quality, classroom climate, and assessment design.

The framework's empirical usefulness would be weakened under several possible findings. For example, CELF would require modification if:

1. Attentional Fragmentation Conditions could not be distinguished reliably from established measures of extraneous cognitive load, interruption, or distraction;
2. Fragmentation indicators consistently failed to predict conceptual continuity or learning outcomes after relevant covariates were considered;
3. Restoration opportunities showed no moderating relationship with cognitively demanding tasks;
4. Cognitive malnourishment provided no incremental explanatory value when examined alongside overload, shallow processing, fatigue, and disengagement;
5. Cognitive endurance was explained fully by sustained attention, self-regulation, persistence, or prior knowledge; or
6. CELF relationships failed to replicate across classrooms, tasks, or student populations.

Conversely, support for CELF would require more evidence that distraction affects performance or that reflection can benefit learning. Stronger support would involve demonstrating that the proposed interaction among CELF's classroom-level dimensions accounts for meaningful variation when established learner-, task-, and instructional-level explanations are also considered, and that its propositions predict outcomes across multiple methods and contexts.

Empirical research may therefore support, narrow, revise, or reject components of CELF. Such outcomes would not represent a failure of the framework's research function. They would clarify its conceptual boundaries, improve measurement, and determine

whether CELF provides a useful classroom-level organization for examining sustained cognition in technology-rich secondary science classrooms.

9. Conclusions

The Cognitive Ecology of Learning Framework (CELF) offers an applied, hypothesis-generating framework for examining the conditions that may support or constrain sustained disciplinary cognition in technology-rich secondary science classrooms. Its central contribution is to connect the intellectual demands of science learning with the attentional and environmental conditions surrounding that work. Through Disciplinary Cognitive Demand, Attentional Fragmentation Conditions, and Restoration Opportunities, CELF provides a shared ecological and temporal frame for examining whether students can remain engaged with complex disciplinary reasoning long enough to interpret evidence, revise explanations, and consolidate understanding.

CELF treats attention as a cognitive process whose sustained deployment may be supported or constrained by interactions among learner characteristics, task demands, instructional organization, environmental stimulation, and opportunities for recovery. It also proposes cognitive malnourishment and cognitive endurance as context-dependent constructs requiring empirical validation. Neither should be interpreted as a diagnostic category, fixed learner trait, or inevitable consequence of technology use. Their value will depend on whether future research can distinguish them from established constructs and demonstrate that they account for meaningful variation when considered alongside established explanations of science learning.

The framework is therefore neither an argument against educational technology nor a prescriptive instructional model. Digital tools may strengthen scientific inquiry when they support coherent disciplinary objectives, just as poorly organized nondigital environments may disrupt conceptual continuity. CELF instead directs attention toward a bounded classroom-level question: whether the instructional ecology enables students to sustain the thinking that meaningful science learning requires. Its propositions must now be tested through direct classroom research, construct validation, comparison with established explanations, and replication across learners and contexts. Ultimately, CELF invites researchers and educators to consider not only what students are asked to learn, but whether the conditions of learning allow them to think deeply enough, and long enough, for understanding to develop.

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Abbreviations

The following abbreviations are used in this manuscript:

CELF	Cognitive Ecology of Learning Framework
CLT	Cognitive Load Theory
ICAP	Interactive, Constructive, Active, and Passive
LMS	Learning Management System

References

- Alexander, P. A. (2005). The path to competence: A lifespan developmental perspective on reading. *Journal of Literacy Research*, 37, 413–436. [\[CrossRef\]](#)
- Altmann, E. M., & Trafton, J. G. (2002). Memory for goals: An activation-based model. *Cognitive Science*, 26, 39–83. [\[CrossRef\]](#) [\[PubMed\]](#)
- Ambrose, S. A., Bridges, M. W., DiPietro, M., Lovett, M. C., & Norman, M. K. (2010). *How learning works: Seven research-based principles for smart teaching*. Jossey-Bass.
- Baddeley, A. D. (1992). Working memory. *Science*, 255, 556–559. [\[CrossRef\]](#) [\[PubMed\]](#)
- Baddeley, A. D. (2000). The episodic buffer: A new component of working memory? *Trends in Cognitive Sciences*, 4, 417–423. [\[CrossRef\]](#) [\[PubMed\]](#)
- Bandura, A. (1986). *Social foundations of thought and action: A social cognitive theory*. Prentice-Hall.
- Bangert-Drowns, R. L., Hurley, M. M., & Wilkinson, B. (2004). The effects of school-based writing-to-learn interventions on academic achievement: A meta-analysis. *Review of Educational Research*, 74, 29–58. [\[CrossRef\]](#)
- Barrett, P., Zhang, Y., Moffat, J., & Kobbacy, K. (2015). A holistic, multi-level analysis identifying the impact of classroom design on pupils' learning. *Building and Environment*, 89, 118–133. [\[CrossRef\]](#)
- Bawden, D., & Robinson, L. (2009). The dark side of information: Overload, anxiety and other paradoxes and pathologies. *Journal of Information Science*, 35, 180–191. [\[CrossRef\]](#)
- Bjork, R. A., & Bjork, E. L. (2011). Making things hard on yourself, but in a good way: Creating desirable difficulties to enhance learning. In M. A. Gernsbacher, R. W. Pew, L. M. Hough, & J. R. Pomerantz (Eds.), *Psychology and the real world: Essays illustrating fundamental contributions to society* (pp. 56–64). Worth Publishers.
- Blakemore, S.-J., & Choudhury, S. (2006). Development of the adolescent brain: Implications for executive function and social cognition. *Journal of Child Psychology and Psychiatry*, 47, 296–312. [\[CrossRef\]](#) [\[PubMed\]](#)
- Boksem, M. A. S., & Tops, M. (2008). Mental fatigue: Costs and benefits. *Brain Research Reviews*, 59, 125–139. [\[CrossRef\]](#) [\[PubMed\]](#)
- Bransford, J. D., Brown, A. L., & Cocking, R. R. (Eds.). (2000). *How people learn: Brain, mind, experience, and school*. National Academy Press.
- Bronfenbrenner, U. (1979). *The ecology of human development: Experiments by nature and design*. Harvard University Press.
- Carr, N. (2010). *The shallows: What the internet is doing to our brains*. W. W. Norton.
- Cepeda, N. J., Pashler, H., Vul, E., Wixted, J. T., & Rohrer, D. (2006). Distributed practice in verbal recall tasks: A review and quantitative synthesis. *Psychological Bulletin*, 132, 354–380. [\[CrossRef\]](#) [\[PubMed\]](#)
- Chi, M. T. H., De Leeuw, N., Chiu, M.-H., & Lavancher, C. (1994). Eliciting self-explanations improves understanding. *Cognitive Science*, 18, 439–477. [\[CrossRef\]](#) [\[PubMed\]](#)
- Chi, M. T. H., Feltovich, P. J., & Glaser, R. (1981). Categorization and representation of physics problems by experts and novices. *Cognitive Science*, 5, 121–152. [\[CrossRef\]](#) [\[PubMed\]](#)
- Chi, M. T. H., & Wylie, R. (2014). The ICAP framework: Linking cognitive engagement to active learning outcomes. *Educational Psychologist*, 49, 219–243. [\[CrossRef\]](#)
- Cowan, N. (2001). The magical number 4 in short-term memory: A reconsideration of mental storage capacity. *Behavioral and Brain Sciences*, 24, 87–114. [\[CrossRef\]](#) [\[PubMed\]](#)
- Craik, F. I. M., & Lockhart, R. S. (1972). Levels of processing: A framework for memory research. *Journal of Verbal Learning and Verbal Behavior*, 11, 671–684. [\[CrossRef\]](#)
- Craik, F. I. M., & Tulving, E. (1975). Depth of processing and the retention of words in episodic memory. *Journal of Experimental Psychology: General*, 104, 268–294. [\[CrossRef\]](#)
- de Jong, T., Linn, M. C., & Zacharia, Z. C. (2013). Physical and virtual laboratories in science and engineering education. *Science*, 340, 305–308. [\[CrossRef\]](#) [\[PubMed\]](#)
- Delgado, P., Vargas, C., Ackerman, R., & Salmerón, L. (2018). Don't throw away your printed books: A meta-analysis on the effects of reading media on comprehension. *Educational Research Review*, 25, 23–38. [\[CrossRef\]](#)
- D'Esposito, M., & Postle, B. R. (2015). The cognitive neuroscience of working memory. *Annual Review of Psychology*, 66, 115–142. [\[CrossRef\]](#) [\[PubMed\]](#)
- DeStefano, D., & LeFevre, J.-A. (2007). Cognitive load in hypertext reading: A review. *Computers in Human Behavior*, 23, 1616–1641. [\[CrossRef\]](#)
- Diamond, A. (2013). Executive functions. *Annual Review of Psychology*, 64, 135–168. [\[CrossRef\]](#) [\[PubMed\]](#)
- Duckworth, A. (2016). *Grit: The power of passion and perseverance*. Scribner.
- Dudai, Y., Karni, A., & Born, J. (2015). The consolidation and transformation of memory. *Neuron*, 88, 20–32. [\[CrossRef\]](#) [\[PubMed\]](#)
- Duschl, R. A. (2008). Science education in three-part harmony: Balancing conceptual, epistemic, and social learning goals. *Review of Research in Education*, 32, 268–291. [\[CrossRef\]](#)
- Engle, R. W. (2002). Working memory capacity as executive attention. *Current Directions in Psychological Science*, 11, 19–23. [\[CrossRef\]](#)

- Eppler, M. J., & Mengis, J. (2004). The concept of information overload: A review of literature from organization science, accounting, marketing, MIS, and related disciplines. *The Information Society*, 20, 325–344. [\[CrossRef\]](#)
- Ericsson, K. A., & Kintsch, W. (1995). Long-term working memory. *Psychological Review*, 102, 211–245. [\[CrossRef\]](#) [\[PubMed\]](#)
- Evans, G. W., & Johnson, D. (2000). Stress and open-office noise. *Journal of Applied Psychology*, 85, 779–783. [\[CrossRef\]](#) [\[PubMed\]](#)
- Fiorella, L., & Mayer, R. E. (2015). *Learning as a generative activity: Eight learning strategies that promote understanding*. Cambridge University Press.
- Fredricks, J. A., Blumenfeld, P. C., & Paris, A. H. (2004). School engagement: Potential of the concept, state of the evidence. *Review of Educational Research*, 74, 59–109. [\[CrossRef\]](#)
- Gazzaley, A., & Nobre, A. C. (2012). Top-down modulation: Bridging selective attention and working memory. *Trends in Cognitive Sciences*, 16, 129–135. [\[CrossRef\]](#) [\[PubMed\]](#)
- Gazzaley, A., & Rosen, L. D. (2016). *The distracted mind: Ancient brains in a high-tech world*. MIT Press.
- Geary, D. C. (2008). An evolutionarily informed education science. *Educational Psychologist*, 43, 179–195. [\[CrossRef\]](#)
- Graham, S., & Perin, D. (2007). A meta-analysis of writing instruction for adolescent students. *Journal of Educational Psychology*, 99, 445–476. [\[CrossRef\]](#)
- Guthrie, J. T., & Wigfield, A. (2000). Engagement and motivation in reading. In M. L. Kamil, P. B. Mosenthal, P. D. Pearson, & R. Barr (Eds.), *Handbook of reading research* (Vol. 3, pp. 403–422). Lawrence Erlbaum Associates.
- Helton, W. S., & Russell, P. N. (2015). Rest is best: The role of rest and task interruptions on vigilance. *Cognition*, 134, 165–173. [\[CrossRef\]](#) [\[PubMed\]](#)
- Hmelo-Silver, C. E., Duncan, R. G., & Chinn, C. A. (2007). Scaffolding and achievement in problem-based and inquiry learning: A response to Kirschner, Sweller, and Clark (2006). *Educational Psychologist*, 42, 99–107. [\[CrossRef\]](#)
- Hockey, G. R. J. (2013). *The psychology of fatigue: Work, effort and control*. Cambridge University Press.
- Immordino-Yang, M. H., Darling-Hammond, L., & Krone, C. R. (2019). Nurturing nature: How brain development is inherently social and emotional, and what this means for education. *Educational Psychologist*, 54, 185–204. [\[CrossRef\]](#)
- Jaakkola, E. (2020). Designing conceptual articles: Four approaches. *AMS Review*, 10, 18–26. [\[CrossRef\]](#)
- Junco, R., & Cotten, S. R. (2012). No A 4 U: The relationship between multitasking and academic performance. *Computers & Education*, 59, 505–514. [\[CrossRef\]](#)
- Kaplan, R., & Kaplan, S. (1989). *The experience of nature: A psychological perspective*. Cambridge University Press.
- Kaplan, S. (1995). The restorative benefits of nature: Toward an integrative framework. *Journal of Environmental Psychology*, 15, 169–182. [\[CrossRef\]](#)
- Kaplan, S., & Berman, M. G. (2010). Directed attention as a common resource for executive functioning and self-regulation. *Perspectives on Psychological Science*, 5, 43–57. [\[CrossRef\]](#) [\[PubMed\]](#)
- Kapur, M. (2016). Examining productive failure, productive success, unproductive failure, and unproductive success in learning. *Educational Psychologist*, 51, 289–299. [\[CrossRef\]](#)
- Karpicke, J. D., & Roediger, H. L., III. (2008). The critical importance of retrieval for learning. *Science*, 319, 966–968. [\[CrossRef\]](#) [\[PubMed\]](#)
- Kintsch, W. (1998). *Comprehension: A paradigm for cognition*. Cambridge University Press.
- Kirschner, P. A., Sweller, J., & Clark, R. E. (2006). Why minimal guidance during instruction does not work: An analysis of the failure of constructivist, discovery, problem-based, experiential, and inquiry-based teaching. *Educational Psychologist*, 41, 75–86. [\[CrossRef\]](#) [\[PubMed\]](#)
- Leroy, S. (2009). Why is it so hard to do my work? The challenge of attention residue when switching between work tasks. *Organizational Behavior and Human Decision Processes*, 109, 168–181. [\[CrossRef\]](#)
- Linn, M. C., Gerard, L., Ryoo, K., McElhaney, K. W., Liu, O. L., & Rafferty, A. N. (2014). Computer-guided inquiry to improve science learning. *Science*, 344, 155–156. [\[CrossRef\]](#) [\[PubMed\]](#)
- Liu, Z. (2005). Reading behavior in the digital environment: Changes in reading behavior over the past ten years. *Journal of Documentation*, 61, 700–712. [\[CrossRef\]](#)
- Lövdén, M., Bäckman, L., Lindenberger, U., Schaefer, S., & Schmiedek, F. (2010). A theoretical framework for the study of adult cognitive plasticity. *Psychological Bulletin*, 136, 659–676. [\[CrossRef\]](#) [\[PubMed\]](#)
- Mangen, A., Walgermo, B. R., & Brønnick, K. (2013). Reading linear texts on paper versus computer screen: Effects on reading comprehension. *International Journal of Educational Research*, 58, 61–68. [\[CrossRef\]](#)
- Mark, G. (2023). *Attention span: A groundbreaking way to restore balance, happiness and productivity*. Hanover Square Press.
- Mark, G., Gudith, D., & Klocke, U. (2008). The cost of interrupted work: More speed and stress. In *Proceedings of the SIGCHI conference on human factors in computing systems* (pp. 107–110). Association for Computing Machinery. [\[CrossRef\]](#)
- Mayer, R. E. (2021). *Multimedia learning* (3rd ed.). Cambridge University Press.
- Means, B., Toyama, Y., Murphy, R., Bakia, M., & Jones, K. (2010). *Evaluation of evidence-based practices in online learning: A meta-analysis and review of online learning studies*. U.S. Department of Education.
- Mercer, N., & Littleton, K. (2007). *Dialogue and the development of children's thinking: A sociocultural approach*. Routledge.

- Miller, G. A. (1956). The magical number seven, plus or minus two: Some limits on our capacity for processing information. *Psychological Review*, 63, 81–97. [\[CrossRef\]](#)
- Moje, E. B. (2008). Foregrounding the disciplines in secondary literacy teaching and learning. *Journal of Adolescent & Adult Literacy*, 52, 96–107. [\[CrossRef\]](#)
- National Research Council. (2012). *A framework for K–12 science education: Practices, crosscutting concepts, and core ideas*. National Academies Press.
- Ophir, E., Nass, C., & Wagner, A. D. (2009). Cognitive control in media multitaskers. *Proceedings of the National Academy of Sciences of the United States of America*, 106, 15583–15587. [\[CrossRef\]](#) [\[PubMed\]](#)
- Osborne, J. (2010). Arguing to learn in science. *Science*, 328, 463–466. [\[CrossRef\]](#) [\[PubMed\]](#)
- Pashler, H. (1994). Dual-task interference in simple tasks. *Psychological Bulletin*, 116, 220–244. [\[CrossRef\]](#) [\[PubMed\]](#)
- Pintrich, P. R. (2002). The role of metacognitive knowledge in learning, teaching, and assessing. *Theory Into Practice*, 41, 219–225. [\[CrossRef\]](#) [\[PubMed\]](#)
- Posner, M. I., & Rothbart, M. K. (2007). Research on attention networks as a model for the integration of psychological science. *Annual Review of Psychology*, 58, 1–23. [\[CrossRef\]](#) [\[PubMed\]](#)
- Raichle, M. E. (2015). The brain's default mode network. *Annual Review of Neuroscience*, 38, 433–447. [\[CrossRef\]](#) [\[PubMed\]](#)
- Ravizza, S. M., Uitvlugt, M. G., & Fenn, K. M. (2017). Logged in and zoned out: How laptop internet use relates to classroom learning. *Psychological Science*, 28, 171–180. [\[CrossRef\]](#) [\[PubMed\]](#)
- Rosen, L. D., Lim, A. F., Carrier, L. M., & Cheever, N. A. (2011). An empirical examination of the educational impact of text message-induced task switching in the classroom. *Educational Psychology*, 31, 793–807.
- Rubinstein, J. S., Meyer, D. E., & Evans, J. E. (2001). Executive control of cognitive processes in task switching. *Journal of Experimental Psychology: Human Perception and Performance*, 27, 763–797. [\[CrossRef\]](#) [\[PubMed\]](#)
- Sana, F., Weston, T., & Cepeda, N. J. (2013). Laptop multitasking hinders classroom learning for both users and nearby peers. *Computers & Education*, 62, 24–31. [\[CrossRef\]](#)
- Sarter, M., Givens, B., & Bruno, J. P. (2001). The cognitive neuroscience of sustained attention: Where top-down meets bottom-up. *Brain Research Reviews*, 35, 146–160.
- Shanahan, T., & Shanahan, C. (2008). Teaching disciplinary literacy to adolescents: Rethinking content-area literacy. *Harvard Educational Review*, 78, 40–59. [\[CrossRef\]](#)
- Simon, H. A. (1971). Designing organizations for an information-rich world. In M. Greenberger (Ed.), *Computers, communications, and the public interest* (pp. 37–72). Johns Hopkins Press.
- Sinatra, G. M., Heddy, B. C., & Lombardi, D. (2015). The challenges of defining and measuring student engagement in science. *Educational Psychologist*, 50, 1–13. [\[CrossRef\]](#)
- Snyder, H. (2019). Literature review as a research methodology: An overview and guidelines. *Journal of Business Research*, 104, 333–339. [\[CrossRef\]](#)
- Steinberg, L. (2005). Cognitive and affective development in adolescence. *Trends in Cognitive Sciences*, 9, 69–74. [\[CrossRef\]](#) [\[PubMed\]](#)
- Strobel, J., & van Barneveld, A. (2009). When is PBL more effective? A meta-synthesis of meta-analyses comparing PBL to conventional classrooms. *Interdisciplinary Journal of Problem-Based Learning*, 3, 44–58. [\[CrossRef\]](#)
- Sweller, J. (1988). Cognitive load during problem solving. *Cognitive Science*, 12, 257–285. [\[CrossRef\]](#) [\[PubMed\]](#)
- Sweller, J., Ayres, P., & Kalyuga, S. (2011). *Cognitive load theory*. Springer.
- Tambini, A., & Davachi, L. (2013). Persistence of hippocampal multivoxel patterns into postencoding rest is related to memory. *Proceedings of the National Academy of Sciences of the United States of America*, 110, 19591–19596. [\[CrossRef\]](#) [\[PubMed\]](#)
- Taylor, T. A. H., Kamel-ElSayed, S., Grogan, J. F., Hajj Hussein, I., Lerchenfeldt, S., & Mohiyeddini, C. (2022). Teaching in uncertain times: Expanding the scope of extraneous cognitive load in cognitive load theory. *Frontiers in Psychology*, 13, 665835. [\[CrossRef\]](#) [\[PubMed\]](#)
- Thomson, D. R., Besner, D., & Smilek, D. (2015). A resource-control account of sustained attention: Evidence from mind-wandering and vigilance paradigms. *Perspectives on Psychological Science*, 10, 82–96. [\[CrossRef\]](#) [\[PubMed\]](#)
- Torraco, R. J. (2005). Writing integrative literature reviews: Guidelines and examples. *Human Resource Development Review*, 4(3), 356–367. [\[CrossRef\]](#)
- Turkle, S. (2015). *Reclaiming conversation: The power of talk in a digital age*. Penguin Press.
- Uncapher, M. R., & Wagner, A. D. (2018). Minds and brains of media multitaskers: Current findings and future directions. *Proceedings of the National Academy of Sciences of the United States of America*, 115, 9889–9896. [\[CrossRef\]](#) [\[PubMed\]](#)
- Vosniadou, S. (2013). Conceptual change in learning and instruction. In S. Vosniadou (Ed.), *International handbook of research on conceptual change* (2nd ed., pp. 11–30). Routledge.
- Winne, P. H., & Hadwin, A. F. (1998). Studying as self-regulated learning. In D. J. Hacker, J. Dunlosky, & A. C. Graesser (Eds.), *Metacognition in educational theory and practice* (pp. 277–304). Lawrence Erlbaum Associates.
- Wolf, M. (2018). *Reader, come home: The reading brain in a digital world*. Harper.

Wolf, M., & Barzillai, M. (2009). The importance of deep reading. *Educational Leadership*, 66, 32–37.

Zimmerman, B. J. (2002). Becoming a self-regulated learner: An overview. *Theory Into Practice*, 41, 64–70. [[CrossRef](#)] [[PubMed](#)]

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