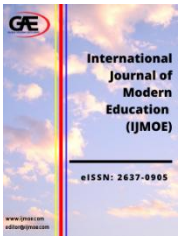
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NEUROPLASTICITY AND CRITICAL THINKING IN HIGHER EDUCATION: BRIDGING BRAIN SCIENCE AND PEDAGOGICAL PRACTICE

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Abstract:

This conceptual paper explores the role of neuroplasticity in the development of critical thinking and pedagogical design in higher education. Neuroscience research has shown that the brain is structurally plastic, which means that it has the ability to change, reorganise, and strengthen its neural connections in response to internal experiences and external stimuli (Gazerani, 2025). There is increasing evidence that neuroplasticity is important for learning, however, current pedagogical frameworks rarely explain how neuroscientific principles can be systematically translated into instructional strategies that promote critical thinking. At present, the widespread adoption of artificial intelligence (AI) has implications for cognitive offloading, the use of external aids to reduce the processing load of a task, and what this might mean for sustained engagement and critical thinking. This paper draws on cognitive neuroscience, critical thinking literature and educational learning theories to propose a four-dimensional neuroplasticity-informed pedagogical framework incorporating Attentional Engagement (The Gateway), Cognitive Challenge (The Stimulus), Reflective Repetition (The Stabiliser) and Emotional and Social Embedding (The Catalyst) to demonstrate that the brain inherently possesses the ability to learn and rewire over time. As critical thinking is considered one of the core outcomes of tertiary education, this conceptual framework can assist educators in developing teaching methods and strategies to enhance and support cognitive development. The paper concludes by discussing pedagogical and institutional implications, limitations, and directions for future research.

Keywords:
Critical Thinking, Educational Learning Theories, Higher Education, Neuroplasticity, Pedagogical Design

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Introduction

This conceptual paper integrates neuroplasticity, critical thinking, and educational learning theories to develop a neuro-pedagogical framework for higher education. Neuro-pedagogy is the systematic integration of neuroscience, cognitive psychology and educational theory in improving teaching and learning. This paper seeks to explain the theoretical relationships between these three domains and proposes a four-dimensional interactive framework incorporating Attentional Engagement (The Gateway), Cognitive Challenge (The Stimulus), Reflective Repetition (The Stabiliser) and Emotional and Social Embedding (The Catalyst) in designing learning experiences that promote sustained cognitive development and the cultivation of critical thinking skills.

Conceptual Approach

This paper employs a theory synthesis approach in line with the typology proposed by Jaakkola (2020). Theory synthesis aims to unify well-established but largely disconnected streams of literature into a coherent conceptual framework that provides new theoretical insights. It does not generate new theories or critically challenge existing ones, but instead synthesises evidence from three domains: neuroplasticity, critical thinking, and educational learning theories, to explain how principles of brain plasticity may inform pedagogical design for the development of critical thinking in higher education.

The literature was identified through a purposive search of peer-reviewed publications and seminal theoretical works and authoritative books in neuroscience, educational psychology, and higher education published in English. Searches were conducted using Scopus, Web of Science, ERIC, PsycINFO, and Google Scholar between January and April 2026. Particular emphasis was placed on foundational studies of neuroplasticity, established theories of learning (including information processing theory, cognitive load theory, constructivism, self-regulated learning, transformative learning, and communities of practice), and contemporary scholarship on critical thinking. Recent publications (primarily from the past 10–15 years) were incorporated to capture current developments while seminal works (Dewey, Piaget, Vygotsky, Atkinson and Shiffrin, Sweller, Zimmerman, and Mezirow) were retained because of their continuing theoretical significance. Studies focusing exclusively on clinical neurorehabilitation or neurological disorders without educational relevance were excluded unless the plasticity mechanism described had clear relevance to learning in non-clinical populations. The selected literature was analysed comparatively to identify conceptual relationships, common mechanisms, and complementary perspectives in the development of the proposed four-dimensional neuro-pedagogical framework.

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Literature Review

What is Neuroplasticity?

Neuroplasticity is the brain's ability to reorganise its structure, functions, and connections in response to internal experiences and external stimuli (Gazerani, 2025). Evrard and Bresciani Ludvik (2023) distinguish several forms of neuroplasticity relevant to the field of education. Synaptic plasticity involves strengthening or weakening connections between neurons, the basis for learning and memory formation. Structural plasticity, which encompasses long-term changes (including dendritic branching and axonal sprouting in specific brain regions), is vital, because acquisition of knowledge and skills is a continuous process. These mechanisms are not passive responses to learning; they are modulated by use, a process known as functional reorganisation.

Synaptic Plasticity

Synaptic plasticity is one of the most important mechanisms underlying neuroplasticity. This refers to the ability of synapses to change in strength over time (Magee & Grienberger, 2020). When two neurons are activated simultaneously, the connection becomes stronger and chemical transformations occur in the synapse that enhance signal transmission. This process, known as long-term potentiation (LTP), is a persistent, long-lasting increase in synaptic strength following high-frequency stimulation. It is regarded as the primary cellular mechanism central to learning and memory (Magee & Grienberger, 2020). A decrease in postsynaptic strength is known as long-term depression (LTD). LTD does not eliminate the synapse; it weakens transmission across it. Both processes are activity dependent. These opposing processes enable the brain to fine-tune its networks. Useful connections are strengthened, and insignificant ones fade. The brain is optimised for the patterns of activity it experiences most frequently. In education, synaptic plasticity underpins cognitive development by shaping learning and memory. This suggests that a sustained, interconnected curriculum is preferable to a series of fragmented modules.

Structural Plasticity

Structural plasticity refers to the physical remodelling of the brain's tissue, involving visible alterations to its anatomical structures. Learning complex skills and navigating new environments can increase the number of connections between neurons and alter grey-matter volume (Draganski et al., 2004). Brain imaging studies indicate that intensive, sustained training is associated with structural differences in skill-related brain regions (Draganski et al., 2004). The educational implications of structural plasticity are twofold. Firstly, the changes reported by Draganski et al. (2004) emerged over weeks of sustained practice, which suggests that the cognitive development sought by higher education must be measured in semesters rather than in single sessions. A curriculum that concentrates on analytical abilities in a single module and then abandons them is unlikely to produce long-term change, however intensive that module may be. Secondly, the study found that once practice ceased, structural gains declined correspondingly, emphasising the need for continuous learning. Hence, institutions of higher learning must design curricula that engage in a continuous cognitive process rather than a one-time instructional activity.

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Functional Reorganisation

Neuroplasticity involves large-scale reorganisation of how functions are distributed across brain regions. It is especially evident in someone who is recovering from a stroke or traumatic brain injury, where surviving neural circuits can assume roles previously performed by the damaged tissue. Pascual-Leone et al. (2005) argued that reorganisation is driven by activity-dependent changes in synaptic strength and connectivity, determined substantially by use. This suggests that teaching should not focus on content alone. Designs that require students to use their critical thinking skills give the relevant neural networks the repeated activation on which reorganisation depends.

What is Critical Thinking?

The concept of critical thinking in education dates back to philosopher and educator John Dewey, who introduced the term 'reflective thinking' (Dewey, 1933). Facione and a panel of 46 experts described critical thinking as "purposeful, self-regulatory judgment which results in interpretation, analysis, evaluation, and inference, as well as explanation of the evidential, conceptual, methodological, criteriological, or contextual considerations upon which that judgment is based" (Facione, 1990a, p. 2). Critical thinking skills are defined as cognitive abilities that enable a person to identify assumptions, evaluate evidence, construct logical arguments, and make informed decisions, while dispositions refer to the consistent internal drive marked by inquisitiveness, open-mindedness, systematicity, non-egocentric processing, introspective reflection, and truth-seeking. Both are fundamental in the development of critical thinkers.

Education systems are widely held to have fallen short in producing critical thinkers, and this remains a challenge for higher learning institutions worldwide (Dumitru & Halpern, 2023). The need to think critically is not new, but it has become pivotal as social media and other mediums of communication have facilitated the deliberate spread of inaccurate or false information (Halpern & Dunn, 2021). Prior studies have indicated that university students in Western Europe, the United States, and Malaysia have low levels of critical thinking skills (Fadhlullah & Ahmad, 2017; Organization for Economic Co-operation and Development [OECD], 2022). In a survey of more than 1,000 business executives and hiring managers, employers ranked the ability to think critically among the capabilities they most value in graduates (Hart Research Associates, 2018). Critical thinking skills help people to solve real-world problems that traditional intelligence metrics fail to capture (Halpern & Dunn, 2021).

Guo et al. (2026) conducted a meta-analysis of critical thinking dispositions among Chinese students between 2000 and 2025, systematically examining sources of heterogeneity across educational stages, disciplinary fields, institutional types, and publication types. Analysing 491 primary studies comprising 688 independent samples and 146,625 participants, the study identified a V-shaped trajectory across grade levels: dispositions decline from elementary through to senior high school, and the opposite outcome is reported for undergraduate and postgraduate students. The findings suggest that repetitive, excessive, and monotonous learning experiences during the K–12 stage may impede the development of critical thinking, and that the subsequent recovery reflects the increased opportunities for critical engagement that higher education provides.

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Critical thinking is not an innate, fixed trait but a set of higher-order cognitive skills that require intentional practice and execution. The 'how' of this mechanism is neuroplasticity. Pedagogical strategies may function as an environmental stimulus that facilitates neural adaptation associated with learning. When students repeatedly engage in critical thinking, behavioural evidence indicates that their reasoning tends to become more systematic and less susceptible to bias. Neuroscientific models attribute such gains to activity-dependent strengthening of prefrontal and associated networks (Immordino-Yang et al., 2019). However, this attribution is inferred from the broader plasticity literature rather than from studies of critical-thinking instruction.

While the developing brain exhibits enhanced plasticity during sensitive periods, the adult brain retains considerable capacity for change. This calls into question deficit models of adult learning and supports a growth-oriented approach to higher education. Like other complex cognitive activities, critical thinking depends on distributed neural networks. No single 'critical thinking centre' has been identified in the brain; however, research has repeatedly implicated several regions. The prefrontal cortex supports executive functions central to critical analysis, including working memory, cognitive flexibility, and inhibitory control (Diamond, 2013). The amygdala–hippocampus–prefrontal circuit jointly supports emotional appraisal, contextual memory, and regulatory control over impulsive or biased responses, while the default mode network has been associated with the internally directed, perspective-taking processes that may be involved in weighing alternative interpretations (Buckner et al., 2008). These networks are not static but evolve through experience.

Pascual-Leone et al. (2005) suggested that repeated engagement of a network strengthens connectivity within and between the regions involved. Extending this to critical thinking specifically remains an inference rather than a demonstrated finding. The principle of 'use it or lose it' applies to critical thinking as it does to other cognitive functions. The weakening of unused connections is relevant in the context of cognitive offloading (Risko & Gilbert, 2016). When analysis, synthesis, and evaluation are routinely delegated to an external system like AI, the circuits that support those operations are activated less frequently. The result is reduced cognitive engagement, which makes offloading a pedagogical problem rather than a technical one.

Despite the considerable scholarly interest in the fields of neuroplasticity, critical thinking, and educational learning theories, existing integrations have not led to an operationalisable proposition-based design framework for critical thinking in higher education. The research on neuroplasticity has mostly examined the biological processes of learning, memory, and neural adaptation (Gazerani, 2025; Magee & Grienberger, 2020), and the research on critical thinking has largely centred around describing the cognitive abilities, dispositions, and teaching strategies associated with critical thinking in an educational setting (Facione, 1990a; Halpern & Dunn, 2021). In turn, such educational learning theories as constructivism, self-regulated learning, cognitive load theory, and transformative learning have usually been investigated as standalone pedagogical models that could explain the process of learning (Mezirow, 2009; Sweller, 1988; Zimmerman, 1990). It should be noted that despite the shared goal of enhancing learning, relatively little attention has been paid to integrating the aforementioned fields into a comprehensive framework for explaining the process of fostering critical thinking through neuroplasticity.

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Addressing this gap, the present conceptual paper proposes an integrated neuro-pedagogical framework comprising four dimensions. Together, these dimensions provide a theoretically grounded explanation of how instructional designs may facilitate neural adaptation while simultaneously cultivating higher-order thinking skills.

Educational Learning Theories

Neuroplasticity and critical thinking can be linked to some of the well-established educational learning theories and integrated into pedagogical design. These theories are selective rather than exhaustive to justify the rationale behind the four dimensions featured in the conceptual framework.

Information processing theory is a cognitive framework in which the mind is described as a system that receives input, processes it through a number of stages, and produces output, with memory acting as the storage supporting each step. Information processing models propose that cognitive abilities are based on the interaction between sensory memory, short-term memory, and long-term memory (Atkinson & Shiffrin, 1968). They work together to encode, store, and retrieve information efficiently. As the brain processes multiple streams of information concurrently, it is imperative to ensure that overloading does not occur. Complementing information processing theory is cognitive load theory, which posits that working memory has a limited capacity. Instructional designs should therefore account for the cognitive demands placed on students, minimising extraneous load and managing intrinsic load so that working memory capacity remains available for germane processing (Sweller, 1988).

Constructivism holds that students actively connect new information to prior knowledge (Piaget, 1970). Piaget saw the individual mind as a primary site of learning. Two students presented with the same information construct meanings differently because their prior knowledge and cognitive structures are distinct. It is closely related to Vygotsky's (1978) zone of proximal development (ZPD), which describes the gap between what a student can achieve independently and what they can accomplish with guidance from educators or more competent peers. Learning is optimised when tasks fall within this zone where support makes the learning objectives attainable.

Self-regulated learning (SRL) describes how proactive students plan, monitor, and evaluate their own progress. The three phases in SRL are forethought, performance, and self-reflection. In the forethought phase, students analyse and plan how to attain their goals; in the performance phase they are involved in the actual execution of the task and in the self-reflection phase students assess their performance of the task (Zimmerman, 1990). SRL is also crucial in the development of metacognitive skills (thinking about thinking) and pedagogical designs. Incorporating scaffolding, systematic self-monitoring, and self-evaluation contributes to improved learning outcomes, personal development, and lifelong learning (Flavell, 1979).

Transformative learning theory describes a process in which students critically examine their assumptions and revise their frames of reference – the mental structures that shape how individuals interpret and understand their experiences and the world around them (Mezirow, 2009). When adult learners are exposed to a new set of rules and expectations, they need to create frames of reference to accommodate the new reality. In addition, knowledge is acquired through participation rather than in isolation, and this connects to communities of practice theory, where learning takes place in a social group with shared goals (Lave & Wenger, 1991).

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Social learning deepens our understanding of the world and exposes us to new opportunities needed for the development and cultivation of critical thinking dispositions.

Proposed Conceptual Framework

A conceptual framework is proposed linking neuroplasticity principles, critical thinking, and educational learning theories. The four dimensions identified are Attentional Engagement (The Gateway), Cognitive Challenge (The Stimulus), Reflective Repetition (The Stabiliser), and Emotional and Social Embedding (The Catalyst). These dimensions are not sequential but interactive. For optimal critical thinking development, all four dimensions need to be addressed simultaneously as shown in Figure 1.

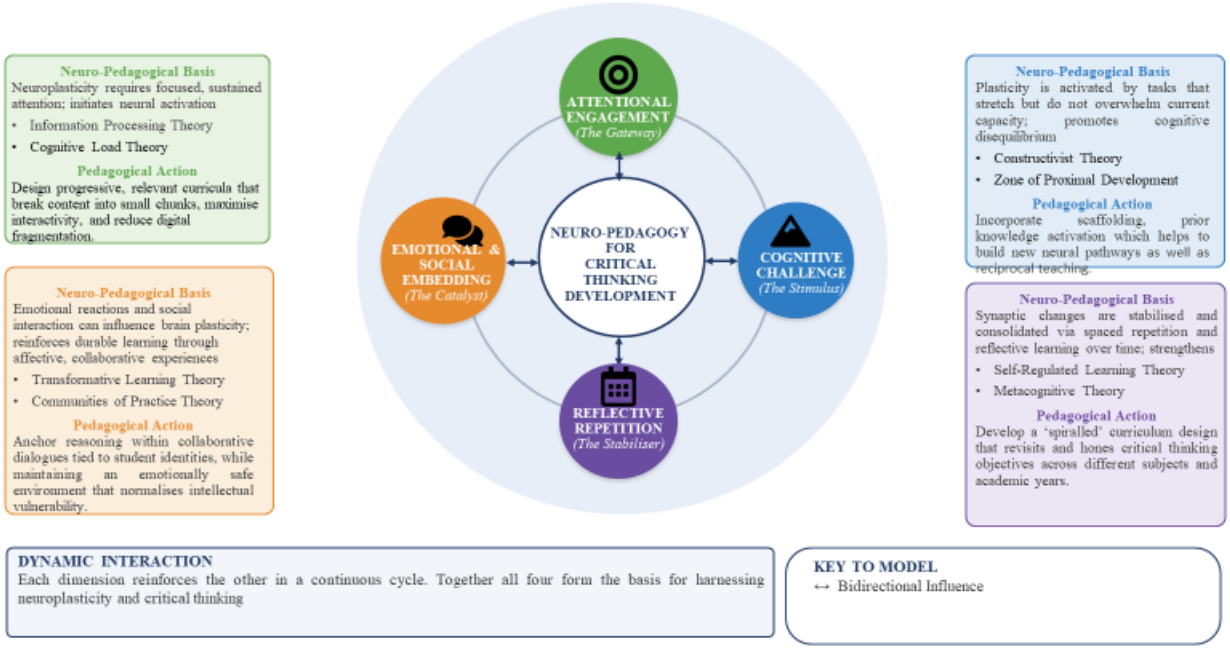


Figure 1: Conceptual Model of the Four Dimensions in Neuro-Pedagogy
Source: Author's framework

Attentional Engagement (The Gateway)

Attentional Engagement serves as a gateway to synaptic plasticity via neuromodulatory systems (Pawlak et al., 2010). It also affects the prefrontal cortex executive functions. These executive processes govern planning, cognitive flexibility, inhibitory control, and reasoning, all of which are the foundation of critical thinking. In information processing theory, attention is the filter that determines which sensory input is allowed into working memory. Encoding into long term memory requires sustained, focused attention. At the cellular level, repeated coordinated activation correlates with long-term potentiation during sustained training. Longitudinal studies have associated this process with structural changes in grey-matter volume (Draganski et al., 2004). The degree to which attentional engagement results in similar structural change in adult learners remains largely inferential.

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Students who remain cognitively engaged are more likely to systematically evaluate evidence, identify logical inconsistencies, and construct well-reasoned arguments. Conversely, insufficient attentional engagement results in superficial learning characterised by memorisation rather than conceptual understanding. In this regard, the cognitive load theory proposes a scientifically grounded method of improving teaching by tailoring instructional designs to the manner in which the human brain processes information (Sweller, 1988). The premise is that working memory is limited very much in capacity and duration and learning is impaired when overload occurs. Research has shown that instructional designs based on cognitive load theory significantly improve learning outcomes in a variety of domains and disciplines (Sweller et al., 2011). Such designs also help to protect attentional capacity from frequent interferences by digital devices. Attentional engagement in educational contexts means more than just keeping students focused. Neuro-pedagogical approaches therefore recommend instructional strategies that sustain cognitive focus through authentic learning tasks, inquiry-based instruction, collaborative discussion, and active participation rather than passive information transfer.

Proposition 1 (P1): Pedagogical designs that sustain attention yield greater development of critical thinking than designs that permit attention to fragment.

Cognitive Challenge (The Stimulus)

One theory that can be linked to cognitive challenge is constructivism (Piaget, 1970). Constructivism is based on the notion that students actively construct knowledge. It advocates that education should focus on problem-solving and critical thinking, encouraging students to connect new information with prior knowledge. Problem-based learning, inquiry-based learning, debates, case analyses, and simulations are pedagogical strategies that activate executive functions, which include reasoning, cognitive flexibility, working memory, and decision-making. Moreover, when students encounter a new task, the brain is forced out of its automated routines, and this effortful processing requires intense neural activity. In the same vein, Vygotsky (1978) defined the ZPD as the difference between present and potential levels of cognitive growth, where students can achieve their learning goals by working with their educators or competent peers without feeling overwhelmed.

Neuroscientific evidence suggests that the brain undergoes structural and functional adaptation when individuals encounter tasks requiring sustained mental effort, complex reasoning, and problem solving. Animal and clinical studies indicate that brain-derived neurotrophic factor (BDNF) supports synaptic strengthening and memory consolidation (Miranda et al., 2019). However, it has not been established whether cognitive challenge produces comparable BDNF-mediated effects in learners.

Proposition 2 (P2): Instructional tasks that require effortful reasoning within ZPD produce greater development of critical thinking than tasks that emphasise factual recall.

Reflective Repetition (The Stabiliser)

Self-regulated learning theory views learning as proactive rather than reactive (Zimmerman, 1990). This theory is based on the premise that students need to use metacognitive strategies to control and regulate their learning effectively. Metacognition is a higher-order thinking process which involves the ability to think, rationalise, assess, and evaluate (Flavell, 1979). It

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describes self-regulated students as metacognitively, motivationally, and behaviourally active participants in their own learning; they plan, organise, self-instruct, self-monitor, and self-evaluate at different stages throughout the learning process (Zimmerman, 1990). They are motivated to see themselves as autonomous, competent, and confident students, as well as having the ability to select, structure, and create environments that optimise learning. Furthermore, spaced repetition supports learning as synaptic changes are stabilised over time (Smolen et al., 2016). Reflective journals, self-assessment, peer feedback, and portfolios encourage students to become aware of how they think. These practices, when intentionally incorporated into course design, enable students to progress from superficial knowledge to a more profound understanding and improved academic performance. This dimension emphasises the need for a curriculum design that embeds critical thinking objectives across courses, offering a wide range of opportunities for practice.

Proposition 3 (P3): Repeated practice combined with structured reflection and formative feedback produces greater development of critical thinking than repeated practice alone.

Emotional and Social Embedding (The Catalyst)

Transformative learning theory highlights the process of creating and redefining the meaning of one's existence (Mezirow, 2009). This theory is especially relevant to adult learning as it invites individuals to interpret experiences in ways that foster autonomous thinking and growth. Transformative learning takes place when students are confronted with situations that challenge their current perspectives and encourage them to critically examine their beliefs. In this context, emotional safety is necessary for truth-seeking and depends on academic environments that embrace intellectual vulnerability. Additionally, the theory of communities of practice refers to groups of people who share common goals or a passion for something they do on a regular basis. In view of this, learning is characterised as legitimate peripheral participation in communities of practice (Lave & Wenger, 1991). Emotionally meaningful experiences and social interaction may influence learning processes that are associated with neuroplasticity. Although the exact mechanisms through which these factors operate in authentic educational settings remain unclear, emotionally supportive and socially interactive learning environments may facilitate learning and cognitive development.

Proposition 4 (P4): Learning environments characterised by psychological safety and collaborative dialogue promote greater development of critical thinking dispositions than environments in which students work in isolation.

Proposition 5 (P5) (Integrated Proposition): The simultaneous presence of Attentional Engagement, Cognitive Challenge, Reflective Repetition, and Emotional and Social Embedding produces greater development of critical thinking than any individual dimension operating in isolation.

Summary of the Four Dimensions

Table 1 summarises the four dimensions of the conceptual framework.

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Table 1: Summary of the Four Dimensions

Dimension	Function	Proposed Neuroplastic Mechanism	Theoretical Foundation	Contribution to Critical Thinking Development
Attentional Engagement	Gateway	Neuromodulatory gating of synaptic plasticity; sustained attention is theorised to support long-term potentiation and encoding.	Information Processing Theory (Atkinson & Shiffrin, 1968); Cognitive Load Theory (Sweller, 1988)	Enhances attentional control, cognitive readiness, and deep information processing.
Cognitive Challenge	Stimulus	Effortful processing and BDNF-mediated signalling are theorised to strengthen synapses and extend neural networks.	Constructivist Theory (Piaget, 1970); Zone of Proximal Development (Vygotsky, 1978)	Develops analysis, evaluation, reasoning, and problem-solving abilities.
Reflective Repetition	Stabiliser	Spaced, repeated practice is theorised to consolidate synaptic change and stabilise learning over time.	Self-Regulated Learning (Zimmerman, 1990); Metacognitive Theory (Flavell, 1979)	Strengthens metacognition, self-regulation, and transfer of knowledge across contexts.
Emotional and Social Embedding	Catalyst	Emotional modulation of memory consolidation; socially mediated learning is theorised to deepen encoding.	Transformative Learning (Mezirow, 2009); Communities of Practice (Lave & Wenger, 1991)	Encourages open-mindedness, perspective-taking, collaborative reasoning, and critical-thinking dispositions.

Source: Author's four dimensions

Note. The mechanisms listed are theorised links between pedagogical design and neural adaptation. They are drawn from laboratory, animal, and clinical plasticity research, and have not been demonstrated directly in higher education classrooms. They are presented as the reasoning behind the propositions rather than as established findings.

Neuro-Pedagogical Design: A Worked Example

The following example illustrates a problem-based module in which students investigate the effects of climate change over one semester (approximately 14 weeks) with two contact hours weekly.

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Attentional Engagement (The Gateway). The module begins with authentic and locally relevant case studies such as coastal erosion, flooding, or extreme weather impacting the nearby communities. Students analyse multimedia resources, scientific reports, government policies, and expert interviews. Learning activities are carefully sequenced to minimise cognitive load and maintain sustained attention through guided questioning, concept mapping, and structured classroom discussions.

Cognitive Challenge (The Stimulus). Students work individually and in groups to examine the causes, effects, and possible solutions to climate-related problems. They evaluate conflicting evidence, compare policy alternatives, identify assumptions, and justify recommendations using scientific data and scholarly literature. Activities such as debates, case analyses, simulations, and policy-design workshops require students to synthesise information, evaluate competing perspectives, and construct evidence-based arguments, thereby engaging higher-order cognitive processes associated with critical thinking.

Reflective Repetition (The Stabiliser). Learning is reinforced through practice and reflection over the semester. Students submit proposal drafts, receive formative feedback from instructors and peers, revise their work, and maintain reflective learning journals documenting how their thinking evolves. Regular self-assessment activities encourage students to evaluate their reasoning strategies, identify misconceptions, and monitor their own learning progress. These repeated opportunities for revision and reflection support deeper conceptual understanding and facilitate the transfer of knowledge across contexts.

Emotional and Social Embedding (The Catalyst). As climate change directly affects students' communities and future livelihoods, the topic provides personal relevance and emotional engagement. Collaborative group work, stakeholder interviews, peer discussions, and presentations to community representatives encourage students to negotiate different viewpoints while developing empathy and perspective-taking. Such socially interactive learning environments create opportunities for meaningful dialogue, motivate and encourage students to connect academic knowledge with real-world challenges (critical dispositions).

These four dimensions interact simultaneously rather than sequentially. Sustained attention enables students to engage with increasingly complex cognitive tasks. Repeated reflection consolidates learning and refines reasoning while emotionally meaningful and socially collaborative experiences reinforce motivation and deeper engagement. This illustrates how neuroplasticity principles may be translated into pedagogical practice to foster the development of critical thinking skills and dispositions in higher education.

Pedagogical Implications

Traditional assessments often measure critical thinking outcomes without providing instruction on them. Translating neuroplasticity principles into curriculum design requires rethinking what is taught and how it is taught. Several evidence-based approaches warrant consideration.

Critical thinking should not be an add-on skill or stand-alone course but embedded across all subjects and courses, with increasing levels of complexity as students progress in their studies. This approach takes advantage of the spacing effect, offering distributed practice that stabilises neural changes (Smolen et al., 2016). It also contextualises critical thinking within disciplinary content, thereby enhancing transferability (Halpern & Dunn, 2021).

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Lecture-based instruction is efficient for the delivery of information but offers little opportunity for the active cognitive engagement that drives plasticity. Problem-solving, discussion, case analysis, and project-based learning require students to generate knowledge, engaging neural circuits that support critical analysis. A meta-analysis of 225 studies found that active learning improved examination performance and reduced failure rates relative to traditional lecturing across science, technology, engineering, and mathematics (STEM) disciplines, with the largest gains in smaller classes (Freeman et al., 2014).

Teaching students how their brains work, including basic principles of learning and metacognition ('thinking about thinking'), can be a tool for increasing motivation and strategy choice. Students who understand that intellectual struggle leads to neural growth may persist through difficulty longer. Meta-analytic evidence indicates small average effects on motivation and achievement, with benefits concentrated among lower-attaining students; the generality of these findings remains contested (Sarrasin et al., 2018).

Inquiry-based learning (IBL) encourages students to construct knowledge by asking authentic questions, formulating hypotheses, investigating evidence, and drawing logical conclusions. Authentic questions engage the attentional and motivational systems that gate plasticity. Reasoning involves the kind of cognitive challenge associated with structural adaptation. Animal and clinical work shows that neurotrophic factors support synaptic strengthening but whether classroom-level cognitive challenge produces similar effects remains to be established (Miranda et al., 2019). IBL without structure (unguided or minimally guided by educators or competent peers) may overwhelm working memory instead of promoting plasticity.

When students are required to articulate, defend, and revise their positions in small-group discussion, multiple neural systems are activated simultaneously, including language production, perspective-taking, conflict monitoring, and reasoning. The social nature of these interactions may enhance emotional engagement and memory consolidation. Structured protocols such as debate, Socratic seminar, and think-pair-share provide frameworks for productive collaboration.

Institutional Implications

If neuroplasticity-informed pedagogy calls for specific instructional approaches, faculty development is vital. Professional development should be both conceptual (the principles of how learning changes the brain) and practical (how to design learning experiences based on those principles). Faculty development in this area should be grounded in scientific evidence or findings as the translation of neuroscience to classroom practice is vulnerable to distortion. Oversimplified or inaccurate claims about the brain are often used to justify ineffective practices (Howard-Jones, 2014).

Critical thinking is often measured by administering standardised tests at a single point in time. These instruments provide useful data but may not assess the process by which critical thinking develops. Assessment approaches that monitor growth over time, encompass multiple aspects of critical thinking (including dispositions), and offer formative feedback to support ongoing development are valuable from the perspective of neuroplasticity. Furthermore, there is longstanding evidence of substantial gains in student achievement through the use of formative assessment (Black & Wiliam, 1998). Higher learning institutions need to understand that

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developing critical thinking is a long-term investment with benefits that are not immediately measurable.

The effectiveness of student-centred learning environments is closely associated with learning methods and their implementation. Smaller classes and more individualised attention seem to support the development of critical thinking with increased opportunities for discussion, feedback, and mentoring (OECD, 2022). However, higher education has been heading towards larger classes and less faculty-student interaction. Institutions that regard critical thinking as a priority should examine resource allocation, which may entail difficult trade-offs but can produce measurable returns in terms of students' cognitive development.

Pathways for Empirical Validation of the Conceptual Framework

The five propositions are intended to serve as a basis for future empirical research rather than to make definitive causal claims. Each proposition can be operationalised using established educational and psychological constructs, and appropriate research designs and measures to facilitate empirical investigation.

Proposition 1 (Attentional Engagement)

Future research could operationalise attentional engagement with behavioural measures (e.g. time-on-task, participation rates), validated student engagement questionnaires, classroom observation protocols, or learning analytics from digital learning platforms. Critical thinking outcomes could be measured using established instruments such as the California Critical Thinking Skills Test (CCTST; Facione, 1990b), Halpern Critical Thinking Assessment (HCTA; Halpern, 2010), or discipline-specific performance assessments. This proposition could be tested in experimental or quasi-experimental research comparing instructional designs that minimise cognitive overload with traditional teaching methods.

Proposition 2 (Cognitive Challenge)

Cognitive challenge can be operationalised as complexity of learning tasks, problem-based learning activities, case analyses, inquiry-based learning, or structured debates. Comparative intervention studies might examine whether instructional activities that require sustained reasoning, evaluation of competing evidence, and evidence-based argumentation result in greater improvements in critical thinking than activities that emphasise factual recall.

Proposition 3 (Reflective Repetition)

Interventions such as reflective journals, self-assessment, peer feedback, and spaced retrieval practice over an academic semester could be used to explore reflective repetition. Longitudinal or repeated-measures designs would allow researchers to see whether repeated practice plus structured reflection results in greater gains in critical thinking than repeated practice alone.

Proposition 4 (Emotional and Social Embedding)

Emotional and social embedding can be operationalised through measures of psychological safety, collaborative learning, classroom climate, and students' sense of belonging. A mixed-methods research design combining validated survey instruments, classroom observations, and

qualitative interviews could be used to explore the influence of emotionally supportive and socially interactive learning environments on the development of critical thinking dispositions.

Integrated Framework (P5)

Future studies should examine the combined effects of the four dimensions as the proposed framework conceptualises them as interactive rather than independent. Structural equation modelling, multilevel modelling, or longitudinal intervention studies could be used to investigate whether the simultaneous presence of all four dimensions explains greater variance in critical thinking development than any individual dimension alone.

Limitations and Future Research Directions

Neuroplasticity has been extensively studied in clinical and experimental contexts, but its application in education calls for further investigation of how the reorganisation of neural networks influences academic achievement and socio-emotional skill development. The specific neural mechanisms underlying the improvement of learning through these strategies need to be identified. The proposed framework synthesises existing literature across neuroscience, critical thinking, and educational theories; however, the five propositions remain to be tested empirically. Traditional instruments do not always capture the benefits of learning based on neuroplasticity, suggesting the need to develop accurate assessment methodologies for knowledge consolidation and long-term retention.

Artificial intelligence (AI) in higher education is gaining momentum, but it also poses significant pedagogical challenges. Over-reliance on AI can be detrimental when students delegate cognitive functions such as remembering, analysing, evaluating, and problem solving to external systems (Risko & Gilbert, 2016). Although cognitive offloading may increase the efficiency of performing routine tasks, it could reduce students' opportunities for sustained mental effort necessary for neuroplastic adaptation which is naturally activity-dependent (Magee & Grienberger, 2020). The educational challenge now is how to embed AI in higher education to augment, not replace, human cognition. Future pedagogical models based on neuroplasticity should therefore consider AI as a pedagogical tool for learning improvement, while ensuring that students receive the constant attention, cognitive challenge, reflective repetition, and emotionally significant interactions that are necessary for the acquisition of solid critical thinking skills.

Longitudinal studies of neural change associated with instruction in critical thinking could provide direct evidence for plasticity-informed pedagogical approaches. Research should also examine whether critical thinking dispositions are as adaptable as critical thinking skills, and which interventions are most effective in promoting their development. As critical thinking is conceptualised and modelled differently from one cultural setting to another, comparative research on how neuroplasticity-informed pedagogies function in diverse cultural settings could shed light on universal principles and culturally specific adaptations.

Conclusion

Critical thinking remains one of the most important educational outcomes of higher education, yet its development requires pedagogical approaches that extend beyond the transmission of disciplinary knowledge. By integrating principles of neuroplasticity with established

educational learning theories, the proposed framework reconceptualises critical thinking as a dynamic and developmental process that is strengthened through sustained cognitive engagement, meaningful challenge, reflective practice, and socially mediated learning. The principal contribution of this paper lies in the development of a four-dimensional neuro-pedagogical framework comprising Attentional Engagement, Cognitive Challenge, Reflective Repetition, and Emotional and Social Embedding. The framework is based on insights from neuroscience, educational psychology and learning theory to give educators a coherent basis to design learning environments that extend beyond knowledge acquisition to deeper cognitive development. Although the proposed framework is conceptual and requires empirical validation, it provides a foundation for future research on the relationships between pedagogical design, neuroplasticity, and critical thinking in diverse higher education settings. In the end, knowing how students learn is just as important as knowing what they learn. Therefore, the integration of neuroscience and pedagogy is not only a new interdisciplinary field of study but also an important move toward building learning environments that enable students to become reflective, critical thinkers.

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