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A Conceptual Framework for Neuropedagogical And Competency-Based Approaches in Engineering Education

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Abstract: This conceptual paper explores the integration of neuropedagogical and competency-based methodologies within engineering education. In this context, the competency-based approach outlines the anticipated professional achievements and the evaluation standards, whereas the neuropedagogical approach specifies the learning conditions necessary to realize these outcomes. Despite typically appearing within the same curriculum, the interaction and integration point between these methodologies are not yet theoretically defined. Through comparative analysis of integration across pedagogical levels, the authors posit that the engineering task stands as the junction connecting both approaches. This convergence is viewed as an advanced integration form, where decision-making in both fields mutually influences task design and evaluation. The paper differentiates between the conditions, principles, mechanisms, and anticipated outcomes of convergence, presenting the mechanism as a hypothesis. Four criteria are suggested for verifying claims of a 'new quality': mutual modification of the two fields, deep integration, distinguishing outcome from process, and drawing meaningful comparisons. This culminates in a theoretical foundation for crafting convergent learning tasks and guiding their empirical investigation.

Keywords: Pedagogical convergence, neuropedagogy, competency-based approach, engineering education, unit of analysis, engineering learning task, cognitive load, constructive alignment.

Introduction: When devising an engineering curriculum, two interrelated questions arise at distinct analysis levels. The first determines the professional tasks a graduate should undertake and to what degree, addressed by the competency-based approach as defined by the International Engineering Alliance (2021) regarding graduate attributes and professional activity. Biggs' methodology advocates for a constructive alignment of learning outcomes with corresponding instructional and evaluative activities, while the CDIO model emphasizes fundamental knowledge through the conception, design, implementation, and operation of products and systems.

The second question pertains to educational neuroscience. The integration of brain, psychology, and instructional research into a unified discipline is noted by the OECD (2007) and Tokuhama-Espinosa (2011). According to Dehaene (2020), four foundational learning pillars include attention, active participation, error feedback, and consolidation. However, critical evaluations indicate that neuroscientific findings cannot be seamlessly applied to instructional design; Bruer (1997) suggests an intermediary role for cognitive psychology, while Howard-Jones (2014) attributes persistent neuromyths to the linguistic and cultural disparities between neuroscience and education.

Pedagogical guidelines often present these approaches adjacent to one another, without elaborating on their interconnections, wherein one chapter outlines competencies and another focuses on "brain-based" methodologies. In such contexts, the prefix "neuro" serves more to justify than clarify. Weisberg et al. (2008) explain that scientific explanations with extraneous neurological data tend to receive higher evaluations from laypeople. A study involving 242 educators in the UK and Netherlands demonstrated that participants, on average, endorsed 49% of the presented neuromyths, with increased neuro-knowledge failing to shield them against these fallacies (Dekker et al., 2012).

The notion of a convergent approach could underpin the amalgamation of these methodologies, yet in educational literature, it holds varying interpretations: developing novel and traditional approaches (Pervova, 2014), and cultivating new education sciences through technical advancements (Mamina, 2022), or rethinking teacher education paradigms (Aleksandrova, 2025). Kondakov and Sergeev (2020) conceptualize a convergent learning environment. While these inquiries link pedagogical convergence and engineering professions (Shtager, 2022; Zhironkina, 2021), the approaches remain categorized separately without defining an analytical unit for integrating neuropedagogical and competency-based methodologies in engineering education or establishing a way to assess the emergent quality from their union.

The article's objective is to examine interpretations of pedagogical convergence, ascertain the analytical unit, conditions, and interactive mechanisms between neuropedagogical and competency-based approaches in engineering education, and to establish testing standards for the "new qualitative value" hypothesis. The discourse addresses: (a) the analytical level of each approach and their connecting segment; (b) what distinguishes convergence from parallel methodologies; (c) what evidence is required to substantiate the "new qualitative value" claim.

METHOD

This study entails a theoretical analysis that draws upon a competency-based approach, constructive alignment, cognitive load theory, and four-component instructional design. The work includes a narrative review of pedagogical convergence publications from 2002 to 2026, noting that conclusions about existing gaps are based solely on the examined sources. Comparisons focus on convergence objects, scale, mechanisms, evidence, and limitations. The definitions and judgment criteria are crafted via conceptual modeling and synthesis.

The Analytical Unit Bridging the Methodologies

Unlike competitive responses, neuropedagogical and competency-based approaches better complement each other at varied educational levels. Therefore, comparative effectiveness analysis is less insightful than focusing on analysis objects, units, explanatory mechanisms, and evidence types (see Table 1).

Table 1

Comparison of the Competency-Based and Neuropedagogical Approaches

Criterion	Competency-based approach	Neuropedagogical approach
Object of analysis	Professional activity and preparation for it (Crawley et al., 2014; International Engineering Alliance, 2021)	The individual learning process (OECD, 2007; Tokuhama-Espinosa, 2011)
Unit of analysis	Observable learning outcome and its assessment criterion (Biggs, 1996)	Attention, working memory, feedback, consolidation (Dehaene, 2020; Sweller et al., 2019)
Key question	What should the student be able to do, under which conditions and to what standard?	Under which cognitive conditions does the learning that leads to this outcome take place?
Type of evidence	Assessment data, accreditation requirements	Neuroscientific findings, cognitive explanation, testing in instructional settings (Bruer, 1997; Thomas et al., 2019)
Risk of misuse	Reducing competence to a list of disconnected skills	Treating a neuroscientific finding as a ready-made classroom rule

(Howard-Jones, 2014; Weisberg et al., 2008)

Both perspectives conceptualize knowledge as observable activity capacity, differing in analytical levels. Competence-based explains professional, normative requirements, while neuropedagogy examines individual learning conditions. Direct combination is unfeasible; thus, an intermediary unit liable to both perspectives is necessary.

In engineering curricula, the engineering learning task is suitable as it represents both the professional activity model and learning context. Aligned with the 4C/ID model, learning tasks, supportive and procedural information, and part-task practice are fundamental (van Merriënboer et al., 2002). Cognitive load theory discusses complex task management and minimizing extraneous presentation-caused load (Sweller et al., 2019). Task structure is pertinent for cognitive theory and professional outcomes.

Neurological evidence needs distinguishing across three levels for educational application. Neurological data don’t prescribe specific classroom tasks; cognitive-pedagogical decisions, real-world testing are essential. Neuropedagogical condition herein pertains to second- and third-level rationale.

Distinguishing convergence from psychological counterparts is crucial. Convergence, in this piece, refers to pedagogical method integration but doesn't involve individual cognitive modes (Jauk et al., 2012).

Convergence Interpretations and Proposed Definition

In a Roco and Bainbridge (2002) report, merging nanotechnology, biotechnology, information technology, and cognitive science (NBIC; ix, 1-2) was advocated. Despite lacking effectiveness evidence, the NBIC concept provides a historical, theoretical backdrop.

The National Research Council's (2014, 17-21) description characterizes convergence as integrating knowledge fields within common frameworks addressing complex issues. The National Science Foundation (n.d.) associates convergence with problem focus and deep discipline integration. While applicable to pedagogical practices, transitioning scientific definitions to education requires theoretical groundwork.

Pedagogical literature offers alternate convergence definitions. Pervova (2014, 73-76) views convergence as traditional-new method relations; Mamina (2022, 6-8) considers it a principle for discipline organization via technical innovations; Aleksandrova (2025, 48, 52, 57-58) differentiates convergent concept and approach, defining the latter as integrating knowledge and technologies. Kondakov and Sergeev (2020, 10, 13-17) propose a convergent environment encompassing educational goals, actors, technological tools, and educational stages. Commonly, convergence implies unification but varies in integration focus: methods, subjects, teacher systems or education environments. Here, convergence focuses on decision sets within learning design and assessment.

Some distinguish convergence by new quality emergence. National Research Council (2014, 43-45) notes systematic interdisciplinary integration yielding results surpassing constituent parts, challenging the "new quality" distinction between integration and convergence. Convergence, thus, may embody deep mutual alignment, problem-focused collaboration, as analyzed (Aleksandrova, 2025; National Science Foundation, n.d.; Zhironkina, 2021). This analytic stance doesn't suggest universal field hierarchies.

Convergence stage distinction isn't qualitative; multidisciplinarity sees separate discipline contributions, interdisciplinarity merges methods, while transdisciplinarity crafts cross-boundary frameworks. Each serves distinct functions (National Research Council, 2014; NSTC, 2022, 13-14). Transdisciplinarity complements, not replaces, disciplinary knowledge—pivotal for engineering education emphasizing foundational mechanics, thermodynamics, or material science expertise.

Cross-language terminology necessitates caution. Lee and Kim (2025) highlight Korean terms variably translated as "convergence," "integrated," and "interdisciplinary" depending on context. Consequently, analysis here emphasizes described activities and outcomes over terminological resemblance.

Thus, a working definition emerges: the convergence of

neuropedagogical and competency-based strategies in engineering education represents deep integration, where learning conditions and professional success criteria intertwine in shared task planning, execution, and assessment, with one approach's decisions altering the other's. This definition narrows broader pedagogical convergence concepts (National Science Foundation, n.d.; Zhironkina, 2021) to engineering and chosen approaches. A common task pinpoints intersection, and decision modification evidences integration depth.

Convergence Conditions, Principles, Mechanism

A definition's utility lies in clarifying conceivable conditions, with engineering education studies partly addressing this issue: Shtager (2022, 157-165) discusses interdisciplinary cycles around technical objects and "concentric discipline;" Zhironkina (2021, 203, 207-208) links educational complexes and collective higher education activity with employer and technological environment demands; Blinova (2018, 44-46) refines engineering study with neuropsychological, cognitive, and information-pedagogical methods.

Connections arise in technical objects, academic-industry collaboration, and learning environments. Yet, direct links between learning conditions and competence criteria remain unexplored. Although piloting is reported by Shtager (2022) and Blinova (2018), participant numbers and comparison designs are undisclosed; thus, these serve as design examples rather than effectiveness evidence.

Analysis categorizes four elements. The condition includes procedure environment and resources; the principle stands as a procedural norm; the mechanism describes operational workflow, while outcomes are forecasted here without empirical verification (see Table 2).

Table 2

Conditions, Principles and Mechanism of Convergence in Engineering Education

Category	Content in engineering education	Basis and status
Conditions	A shared technical object or task with real constraints	Shtager (2022)
	An observable outcome criterion with aligned learning activity and assessment	Biggs (1996); International Engineering Alliance (2021)
	A learning environment with tools for diagnostics and feedback	Blinova (2018)
	Alignment of schedules, incentives and resources for the teaching team	Strimel et al. (2026)
Principles	Problem orientation	National Science Foundation (n.d.)
	Preservation of the disciplinary base	NSTC (2022)
	Reflective iteration: performing, critically reviewing and revising	Astreiko and Lukashenya (2025, pp. 9–10)
	Matching task complexity to students' prior knowledge and working-memory capacity	Sweller et al. (2019); van Merriënboer et al. (2002)
Mechanism	The outcome criterion changes the stages of the task, and the conditions of learning change the assessment procedure	Author's hypothesis; not tested
Expected outcome	Independent, justified decision-making in a new engineering task	Expectation; requires empirical testing

The conjectured mechanism is illustrated through an intended outcome: 'Students justify material choice for a component by calculations and standards.' Constructive alignment predicates corresponding learning and assessment activities (Biggs, 1996). According to cognitive load theory, coordinating technical specifications, formulas, and criteria within high-interactivity tasks may overload novices' working memory (Sweller et al., 2019). The 4C/ID model suggests maintaining task integrity while gradually increasing complexity and providing timely information (van Merriënboer et al., 2002).

The two methodologies, when unlinked, might coexist on a single page independently. Cognitive analysis modifies task structures and intermediate stages, impacting competence evaluation methods; intermediate level justification quality is scrutinized along with final solutions. The mechanism remains a hypothesis, requiring empirical substantiation.

Barriers to this process include semantic variation across authors (Lee & Kim, 2025). Simplification of neuroscience in classrooms often perpetuates neuromyths (Dekker et al., 2012; Howard-Jones, 2014). Cross-disciplinary cooperation necessitates institutional alignment of schedules, incentives, and resources (Strimel et al., 2026). In the course depicted by Bourne et al. (2025), students observed instructor collaboration; teaching team integration does not ensure corresponding student activity integration. Herr et al. (2019) also identify interdisciplinary communication hurdles and educator preparation as distinct international concerns.

New Qualitative Value Criteria

Convergence-related publications frequently employ vague statements like "synergistic effect emerged" or "disciplinary boundaries dissolved," which fail to clarify integration specifics, resultant changes, or emergent phenomena. Sources examined assert that convergence terminology alone doesn't assure new subject areas, quality shifts, or superior educational outcomes (Bourne et al., 2025; Mamina, 2022; National Research Council, 2014; Strimel et al., 2026). Thus, the "new qualitative value" requires scientific validation beyond mere claim.

This validation occurs at two levels. Conceptual value pertains to explanatory and pedagogical opportunities within convergent design, absent in isolated approaches, subjected to theoretical analysis and planning comparison. Educational value emerges through student learning outcomes, necessitating empirical data for affirmation. This article addresses the former level and proposes four criteria for empirical verification.

Criterion one involves mutual modification. Design should explicitly show alteration of one level's decisions based on another's demands; modifying task stages according to cognitive needs or altering grading due to competence criteria exemplifies this.

The second criterion is integration depth, gauged by shared problem definition, conceptual consistency, task co-development, and design decision interdependence. Merely labeling something as interdisciplinary or thematically unified doesn't reflect interaction depth (NSTC, 2022, 10-17).

The third criterion involves distinct results and processes. Course execution, positive student evaluation, and independent knowledge application are three distinct outcomes. Questionnaires measure approach familiarity and preference, not learning outcomes (Astreiko & Lukashenya, 2025; Chervonnyi & Vlasova, 2022). Evidence of educational value emerges from students' independent application of knowledge to new engineering tasks.

The fourth criterion demands relevant, comparative benchmarks. Comparing convergence-taught classes to standard lectures might not elucidate whether outcomes arise from activity, time, or resource differences. Competency-based or problem-based models offer more meaningful comparisons. These criteria collectively relate evidence requirements to certainty levels (see Table 3).

Table 3

Claims About Convergence and the Evidence They Require

Level of claim	Example statement	Evidence required
Conceptual proposal	“It is proposed to organise …”	Comparison of sources and logical argument
Presence of convergence in a design	“The task links decisions of the two approaches”	Document analysis against Criteria 1 and 2; inter-rater agreement
Change in process	“Students began to use intermediate justification sooner”	Observation and process data
Educational value	“The convergent design improves transfer”	Criteria 3 and 4: comparative design, delayed measurement

Additionally, the epistemological foundation preservation between both approaches remains an unresolved question. Even if a shared language is developed, theoretical differences require transparent resolution (Morgan et al., 2026). In engineering education, this entails ensuring neuropedagogical factors don't surpass professional standards, nor do competence criteria inherently secure learning conditions.

CONCLUSIONS

Analysis reveals that neuropedagogical and competency-based approaches target disparate engineering education levels. The former establishes learning conditions, while the latter dictates professional norms. Their union isn't a mechanical theory merge, but an alignment of multi-level design decisions.

Three conclusions follow. First, engineering tasks, rather than subjects or technology, serve as apt analytical units for approach integration, combining professional models with learning environments. Second, mutual decision modification distinguishes convergence between the approaches. Third, "new quality" isn't an inherent convergence result, necessitating separate scholarly and pedagogical application alongside four criteria.

This article's contribution is conceptual, offering a working convergence definition for engineering, distinguishing convergence conditions, principles, mechanisms, and a tool linking claim levels to evidence requirements. This tool aids in convergent activity design in engineering and curriculum analysis claiming convergence. The study refrains from conclusions on educational effectiveness.

Two research avenues arise from the analysis. One involves criterion reliability for mutual influence and integration depth through independent rater consensus on design documents. The second compares convergently designed versus purely competence-based tasks in student-executed new design tasks, maintaining constant time, resources, and problem content across groups. Valid conclusions on convergence efficacy hinge on these controlled conditions.

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