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RESEARCH ARTICLE

UNIVERSAL DESIGN FOR LEARNING: BIOLOGICAL FOUNDATIONS OF COGNITIVE DIVERSITY

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Abstract

Universal Design for Learning (UDL) is increasingly described as a neuroscientifically grounded framework for inclusive education, yet much of this grounding relies on sources produced by UDLproponents, creating a circularity that limits independent credibility. In this paper, researcher addresses that gap. The paper first establishes the neuroscientific evidence for meaningful individual variability across recognition, strategic, and affective neural systems using research entirely independent of UDL, drawing on Finn et al.'s (2015) connectome fingerprinting studies, Miyake et al.'s (2000) landmark analysis of executive function separability, and Pessoa's (2008) synthesis of emotion-cognition integration. It then connectshow UDL'sthree principles: multiple means of representation, action and expression, and engagement, directly reflect and operationalise those findings. The paper argues that UDLis not preference-based accommodation but a principled pedagogical response to the documented architecture of human cognitive variability. Limitations of the current effectiveness evidence base and directions for future research are discussed.

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Introduction:-

Education systems have long operated on an implicit assumption of cognitive uniformity that learners presented with the same instruction will process it through broadly comparable mechanisms and achieve comparable outcomes. Decades of neuroscientific research have dismantled that assumption. Human brains do not process information uniformly; they manifest systematic, biologically grounded variability in the neural pathways underlying recognition, strategic planning, and affective engagement (Finn et al., 2015; Miyake et al., 2000; Pessoa, 2008). Crucially, this variability is not abnormal. It is a fundamental feature of the human nervous system.Universal Design for Learning (UDL) began with a simple idea borrowed from architecture: when you build a ramp for wheelchair users, it also helps parents with pushchairs, delivery workers, and cyclists. Designing for people with specific needs often makes things better for everyone (Rose & Meyer, 2002). UDL applies this same thinking to education. Instead of designing lessons for an "average" student (who doesn't really exist), teachers design for the full range of how people learn and in doing so, help all students more effectively (CAST, 2018).

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UDL is built around three core principles (CAST, 2018):

- Representation — how information is presented (text, audio, visuals, etc.)
- Action & Expression — how students show what they know (writing, speaking, drawing, etc.)
- Engagement — what motivates students and keeps them focused

Two interrelated points motivate this paper. First, the prevailing position in inclusive education holds that there is no one-size-fits-all approach to teaching, and that flexibility built into the initial stages of lesson planning benefits all learners (Rose & Meyer, 2002). Second, and more critically, UDL is currently accepted largely as a normative framework — that is, one that prescribes what teachers should do on the grounds of equity and inclusion values, rather than explaining why or how it works at the level of human cognition. If, however, UDL's three-principle structure genuinely reflects neural architecture rather than pedagogical preference alone, it shifts from a values-based justification to one grounded in how human brains actually vary, giving it descriptive and predictive power that values-based justification alone cannot provide.

Articulating this shift requires more than citing neuroscientific research referenced by UDL advocates about UDL-relevant systems. It requires establishing whether independent neuroscientific research, developed without reference to any educational framework, converges on the same structural conclusions and that is the central aim of this paper. This paper undertakes that connective work: tracing the structural correspondence between independently established neuroscientific findings and UDL's three-principle framework. Section 2 establishes the biological basis of cognitive diversity from independent neuroscientific literature. Section 3 explores how each UDL principle aligns with those findings. Section 4 addresses limitations, and Section 5 draws conclusions and identifies directions for future research.

The Biological Basis of Cognitive Diversity:-

Before exploringUniversal Design for Learning (UDL), it is essential to establish what neuro-science tells us independently, about how individuals differ in cognition. The evidence falls across three functionally distinct but interacting domains: recognition, strategic and affective.

Recognition Networks: How Individuals Differ in Perceiving and Processing Information:-

How individuals perceive and make sense of incoming information is not uniform across people, nor is that variability without pattern, it is systematic and person-specific. Finn et al. (2015) provided striking evidence for this using functional Magnetic Resonance Imaging (fMRI)data from 126 participants across multiple sessions. They demonstrated that each individual's pattern of functional brain connectivity is distinctive and stable enough to serve as a neural 'fingerprint', identifying the same person across entirely different cognitive tasks with high accuracy. The regions showing the greatest individual specificity included visual processing areas and networks central to recognition and perceptual integration.This finding carries a direct educational implication: if the neural architecture supporting recognition is systematically person-specific, then identical instructional stimuli will not be processed identically across learners. Schaefer et al. (2018) extended this work by showing that individual connectivity differences predict performance differences across cognitive tasks, confirming that neural individuality is functionally consequential, not merely structural.Individual variability also extends to how learners integrate information across sensory channels. Superior temporal sulcus regions involved in audiovisual integration show substantial between-person variability in activation (Beauchamp, 2005; Calvert & Thesen, 2004), and individuals differ significantly in how much they rely on visual versus auditory channels during comprehensiondifferences that are partly mediated by neural rather than purely strategic factors (Mayer, 2009). The upshot is clear: there is no representational format that is optimally accessible for all learners simultaneously.

Strategic Networks: How Individuals Differ in Planning, Focusing and Self-Regulation:-

One of the most well-supported areas of research on how people think differently from one another concerns executive function the mental processes we use to plan ahead, stay focused on a goal, switch between tasks, and catch and correct our own errors. Importantly, this research comes from cognitive science, not from educational theory.In a landmark study, Miyake and colleagues (2000) tested 137 college students to understand how three key executive functions relate to each other.

The three functions they examined were:

- the ability to shift mental focus (switching smoothly between different tasks or rules),
- the ability to update working memory(revising what you're holding in mind as new information comes in), and

- the ability to inhibit automatic responses (resisting the urge to do something habitual when the situation calls for something different).

Their key finding was that these three abilities are related but distinct.Individuals who perform well on one component tend to perform somewhat better on the others, though the relationship is imperfect. Treating them as a single, unified ability turns out to be a poor fit for the data. Each function varies independently across individuals, and each contributes to complex thinking in its own way, even after accounting for general intelligence.This finding has held up consistently across two decades of subsequent research (Friedman & Miyake, 2017). There appears to be a shared foundation underlying all three abilities, but updating memory and switching focus each have their own distinct influences, shaped differently by genetics, environment, and development.The educational implications are meaningful and concrete. A learner who is strong at updating working memory but weak at shifting focusmay perform well when permitted to maintain a single approach, but encounter difficulty when required to switch strategies rapidly.

Conversely, someone who is good at blocking out distractions but less skilled at updating may hold onto an earlier, incorrect answer even when new information should prompt them to revise it. These are not differences in effort or motivation — they reflect genuinely distinct cognitive abilities that develop along different timelines and respond differently to how instruction is designed.A related study by Shipsteadet al. (2012) added another layer to this picture by separating two aspects of working memory: holding information active versus letting go of information that is no longer relevant. Interestingly, people who are very good at releasing outdated informationmay inadvertently retain outdated mental representations that interfere with new learning. Meanwhile, those who are good at maintaining information may inadvertently carry outdated mental representations that get in the way of new learning. Because learners vary across all of these dimensions simultaneously, no single format of instruction or expression will work equally well for everyone.

Affective Networks: How Emotion and Motivation Shape Cognitive Processing:-

The third domain concerns how affective states shape cognitive processing. The traditional view of emotion as a separate system that occasionally interferes with cognition has been substantially revised. Pessoa (2008) synthesised neuroimaging evidence to argue that cognitive and emotional processing are deeply integrated at the level of neural circuitry: the amygdala, long considered a fear centre, is modulated by top-down attentional and cognitive factors; the lateral prefrontal cortex, associated with working memory, processes both cognitive variables and affective information simultaneously. Neither system operates independently of the other under normal conditions.Individual differences in this emotion-cognition integration are substantial and consequential. Depue and Collins (1999) documented those individual differences in dopaminergic tone and receptor sensitivity, partially heritable neurobiological variation, produce genuine differences in approach motivation, reward sensitivity, and the capacity to sustain goal-directed effort against competing demands. These are not personality traits that can be overridden by instruction; they are features of the neural architecture through which reward signals modulate cognitive engagement.The practical implication is significant: learners for whom a task or format activates avoidance-related affective circuits will not simply process content less efficiently — the affective response will reshape the cognitive processing itself, altering attention allocation, working memory engagement, and ultimately retention. This provides a neuroscientific basis for treating motivational design not as an optional enhancement but as a fundamental determinant of whether learning occurs at all.

Cognitive Diversity as Biological Normality:-

Research across multiple areas points to the same conclusion: the wide variation we see in how people think and learn is a natural feature of the human brain, not a sign that something has gone wrong (Kovacs & Conway, 2016). Why do people think so differently?Process Overlap Theory helps explain this (Kovacs & Conway, 2016). Rather than the brain having separate, fixed "modules" for different tasks, most mental tasks actually draw on overlapping sets of brain processes. Think of it like tools in a toolbox — different jobs need different combinations of tools, and some tools get shared across many jobs.

Because of this:

- Tasks that share many of the same processes tend to produce similar performance levels in the same person
- Tasks that share fewer processes can produce very different performance levels in the same person
- This is why someone might excel at maths but struggle with reading, or vice versa — it's simply a reflection of their brain's particular strengths

What this means for education:-

Designing lessons for a so-called "average" learner is not just unfair, it's scientifically inaccurate (Kovacs & Conway, 2016). No such average learner exists in reality. Every person has an uneven cognitive profile, with areas of strength and areas of difficulty, and that variability is entirely normal.

Universal Design for Learning(UDL) Principles and Their Neuro-scientific Alignment:-

The neuroscientific evidence reviewed in Section 2 was developed entirely without reference to UDL, emerging from cognitive psychology laboratories, neuroimaging studies, and affective neuroscience research. That three independent lines of inquiry converge on precisely the same three domains — recognition, strategic, and affective processing — that UDL's framework addresses is not coincidental. It reflects the fact that these constitute genuinely distinct but interdependent dimensions of human cognition. Each of UDL's three principles can therefore be understood not as a pedagogical preference but as a direct pedagogical response to a documented feature of neural architecture.

Multiple Means of Representation:-

UDL’s first principle holds that learners benefit from encountering information in multiple formats and modalities, and that instructional design should not privilege a single representational channel. The neuro-scientific rationale follows directly from the perceptual variability established in Section 2.1.Given that individuals possess distinct, stable patterns of neural connectivity in recognition-relevant networks (Finn et al., 2015), different representational formats will be differentially accessible across learnersnot because of deficits, but because of genuine architectural differences in how visual, auditory, and language processing networks are organised and integrated. A learner whose neural organisation efficiently supports sequential verbal processing may struggle with spatially organised visual diagrams, and vice versa. Research on multimedia learning supports this: combining verbal and visual information reduces cognitive load and improves comprehension for some learners while introducing integration demands that impair others, depending on individual differences in working memory capacity and dual-channel processing efficiency (Mayer, 2009).The principle of multiple means of representation is therefore not a matter of catering to preferences. It addresses genuine variation in perceptual-neural architecture, and it reflects the neuro-scientifically grounded insight that systematically varying representational formats increases the probability that each learner will encounter content structured in a way that aligns well with their individual neural organisation.

Multiple Means of Action and Expression:-

The second UDL’s principle holds that learners should have diverse means through which they can act on content and express understanding. Its neuroscientific basis lies in the executive function variability established in Section 2.2.Since shifting, updating, and inhibition are separable capacities with distinct individual-difference profiles (Miyake et al., 2000), any single mode of expression will engage a particular configuration of these functions, rewarding learners whose executive profile happens to match that configuration, and disadvantaging those whose knowledge is equally strong but whose executive architecture differs. A written essay privileges updating and output-monitoring; an oral presentation privileges rapid shifting and inhibitory control under social pressure; a portfolio privileges planning and goal maintenance. None is a purer measure of underlying understanding than the others. Each simply activates a different subset of the executive function repertoire.

Providing flexible means of expression: including iterative, modular, or scaffolded formats, directly addresses working memory architecture as described by Shipstead et al. (2012), rather than simply accommodating preference. Similarly, Universal Design for Learning (UDL) explicit recommendation that instructional scaffolds support metacognitive monitoring reflects neuroscientific evidence that metacognitive capacities are themselves prefrontally mediated executive functions (Fleming et al., 2012) that vary alongside the broader executive function landscape documented by Miyake et al. (2000). Scaffolding metacognition is therefore not supplementary support; it addresses neural variability in the supervisory systems that underpin self-regulated learning.

Multiple Means of Engagement:-

The third Universal Design for Learning (UDL) principle addresses motivational and affective dimensions of learning, recommending diverse means of engaging interest, sustaining effort, and supporting self-regulation. Its neuroscientific basis is the most complex because it concerns the integrated emotion-cognition system described in Section 2.3.Pessoa's (2008) analysis is directly relevant here. If affective and cognitive processing are integrated at the level of neural circuitry, then the motivational context of a learning task is not separable from the cognitive processing it requires. Learners whose neural reward system generates approach-related motivational states in

response to a task will engage prefrontal working memory and strategic resources more effectively than those for whom the same task activates avoidance or anxiety. This is not a willpower difference, it reflects the neurobiological reality that dopaminergic and limbic systems directly influence prefrontal cortex function (Depue & Collins, 1999).
Self-Determination Theory (Deci & Ryan, 2000) complements this at the psychological level. The theory holds that engagement is sustained when instruction supports autonomy (volition and self-direction), competence (experience of effectiveness), and relatedness (meaningful social connection). These psychological constructs map onto the neuroscientific picture: autonomy-supportive environments reduce threat-related amygdala activation that suppresses prefrontal function (Legault & Inzlicht, 2013), while competence experiences activate reward circuitry, reinforcing approach motivation.

It should be noted that the affective dimension of UDL is where the distance between neuro-scientific evidence and specific instructional recommendations is widest. While the science of emotion-cognition integration is well established, translating it into precise classroom prescriptions for diverse contexts remains an open empirical question. UDL provides a principled direction; the specific means of engagement effective for particular learner populations in particular domains requires ongoing, context-sensitive investigation.

Limitations:-

Several important limitations constrain the claims made here:-

First, demonstrating alignment between neuroscientific evidence and UDL's framework establishes a logical connection but not causal proof. The neuroscience establishes the problem: that learners differ meaningfully across recognition, strategic, and affective domains but does not uniquely specify UDL as the solution. Alternative frameworks could, in principle, respond to the same evidence with different pedagogical recommendations.

Second, the empirical evidence base for UDL's effectiveness in improving learning outcomes remains underdeveloped. Systematic reviews (Rao et al., 2014; Capp, 2017) have found encouraging evidence that UDL-informed practices improve engagement and access, but the rigorous experimental studies needed to establish causal effectiveness across diverse populations and contexts remain limited. The neuroscientific grounding this paper establishes is a principled foundation for the framework, not a substitute for outcome research.

Third, the translation gap between neuroscientific findings and specific instructional recommendations is real and not fully bridged here. Knowing that executive functions are separable and individually variable tells us why multiple means of expression are needed in principle; it does not specify what those means should be in any particular domain or age group.

Fourth, the executive function literature reviewed relies primarily on adult and young adult participants. Developmental trajectories of executive function, working memory, and emotion-cognition integration differ substantially from mature adult profiles (Best & Miller, 2010), and UDL is applied across all age ranges. Age-specific elaboration of the neuroscientific basis is needed.

Finally, this paper has not addressed the social and cultural dimensions of learning variability, which interact with neural variability in complex ways. Cultural context shapes what counts as effective representation, expression, and engagement in ways that neuroscience alone cannot specify (Rogoff, 2003). A complete account of UDL's foundations would need to integrate social and cultural evidence alongside neural evidence.

Conclusion:-

This paper has aimed to justify that Universal Design for Learning's three-principle framework has genuine independent neuroscientific support. By establishing the evidence for perceptual-neural variability (Finn et al., 2015), executive function variability (Miyake et al., 2000; Friedman & Miyake, 2017), and affective-cognitive integration variability (Pessoa, 2008; Depue & Collins, 1999) from sources entirely outside the UDL literature, and then demonstrating the structural alignment between these findings and UDL's three principles, the paper addresses the circularity problem that has weakened previous neuroscience-to-UDL arguments.The conclusion is not that UDL is definitively proven effective, the effectiveness evidence base remains nascent, but that it is principled: its structure reflects a genuine and independently documented architecture of human cognitive variability. Learners differ in how they perceive and recognise information, in how they plan, monitor, and express understanding, and in what affective and motivational conditions sustain cognitive engagement. These differences are not deviations from a neurobiological norm. They are the norm.Educational systems that design instruction for a hypothetical average learner, relying on single representational formats, single modes of expression, and uniform motivational structures, are not merely inequitable. They are biologically inaccurate. UDL offers a framework for responding more accurately to the population that education serves

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