NEURO-ECOLOGICAL DYNAMICS IN DIGITAL SECOND LANGUAGE ACQUISITION: INVESTIGATING THE COGNITIVE–ENVIRONMENTAL INTERPLAY IN TECHNOLOGY-MEDIATED LEARNING

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ABSTRACT

This study investigates the neuro-ecological dynamics of digital second language acquisition (SLA), focusing on the interaction between learners' cognitive processes and technology-mediated environments. Drawing on cognitive neuroscience, ecological psychology, and SLA research, we conceptualize digital language learning as a co-adaptive system, where neural mechanisms and environmental affordances continuously influence one another. Through a synthesis of neuroimaging, behavioral, and ecological data, we show that multimodal digital tools such as immersive simulations, gesture-based interactions, and adaptive feedback enhance neuroplasticity and support embodied cognition. The findings highlight that digital SLA extends beyond traditional cognitive processes, engaging sensorimotor, attentional, and emotional networks in dynamic coupling with the digital learning environment. Based on these insights, the paper proposes design principles for neuro-ecologically informed digital learning tools and identifies avenues for future research integrating neurocognitive, ecological, and learning analytics approaches. These results have implications for developing more effective, learner-centered digital language environments that align with the brain's adaptive capacities.

Keywords: Neuro-ecological theory; digital second language acquisition; embodied cognition; neuroplasticity; technology-mediated learning; ecological psychology; multimodal interaction; adaptive learning environments; cognitive neuroscience; brain–environment coupling.

1. INTRODUCTION

1.1 Background of the Study

In the last decade, the digital revolution has fundamentally reshaped the landscape of second language acquisition (SLA). Where language learning was once predominantly confined to physical classrooms, textbooks, and structured teacher-led instruction, learners now engage with dynamic digital environments that span mobile applications, adaptive platforms, virtual reality, and social media. These technological advances have expanded opportunities for engagement and interaction, creating a new learning ecology in which learners can access input and practice at any time and in diverse contexts (Zhu, Zhang, & Irwin, 2024). The proliferation of digital platforms has thus altered not only how learners access language but also how they process and internalize linguistic information.

The integration of digital tools into SLA reflects a broader shift in how the field conceptualizes the learner's environment. Traditional models often treated the learning environment as a passive backdrop for cognitive processes. In contrast, contemporary perspectives suggest that

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digital platforms actively participate in shaping attention, motivation, and engagement, offering affordances that influence both cognitive and neural mechanisms (Nguyen & Doan, 2025). For example, adaptive feedback systems, gamified exercises, and multimodal inputs provide learners with interactive opportunities that can accelerate acquisition while promoting sustained engagement. These developments underscore the transformative impact of digital technologies on the nature and scope of language learning.

The evolving role of Information and Communication Technology (ICT) in education raises a critical debate about whether it serves as an enhancer of learning or a potential replacement for teachers. While ICT has undeniably transformed education by improving access to information, fostering interactive learning, and accommodating diverse learner needs, it cannot replicate the essential human elements that define effective teaching. Mentorship, emotional intelligence, and moral guidance qualities inherent in teachers remain beyond the reach of technological systems. Overreliance on ICT, as the study cautions, risks depersonalizing the learning experience and weakening the teacher–student relationship if not balanced with human engagement. The study ultimately argues that ICT should be strategically integrated to complement, rather than replace, teachers' expertise, creativity, and emotional connection, ensuring that technology enriches rather than diminishes the human dimension of education (Langat, 2025).

The emergence of these digital affordances has prompted a re-evaluation of established SLA theories. Historically, cognitive approaches emphasized internal processes such as working memory, attention control, and information processing capacity, often under conditions relatively isolated from environmental influences. While these frameworks provided foundational insights into the mechanisms of learning, they often overlooked the dynamic interplay between learners and their surroundings. The increasing integration of digital tools necessitates a more nuanced framework that accounts for the reciprocal interactions between learner, technology, and context (Wang, Zhang, & Long, 2022).

This shift aligns with the growing interest in embodied and neuro-ecological perspectives on learning. Embodied cognition posits that cognitive processes are deeply rooted in bodily interactions with the environment, suggesting that learning involves sensorimotor engagement as well as neural adaptation (Britz et al., 2024). In the context of SLA, this implies that language acquisition is not merely an abstract computational process but a situated, interactive phenomenon in which the learner's body, neural systems, and environmental context are interdependent. Digital environments, by facilitating multimodal interaction, extend the scope and richness of these embodied experiences.

Neuro-ecological frameworks further integrate cognitive and environmental perspectives by emphasizing how neural systems and external contexts co-adapt during learning. From this standpoint, the digital learning environment is not neutral; it actively shapes cognitive processing and neural engagement through affordances such as interactive exercises, immediate feedback, and multimodal input (Nguyen & Doan, 2025). These interactions highlight the necessity of reconceptualizing SLA as a system in which brain, body, cognition, and environment function in a dynamic, mutually influential network.

The increasing prevalence of mobile-assisted and immersive learning technologies has also transformed the spatial and temporal dimensions of SLA. Learners can now interact with linguistic content beyond the confines of traditional classrooms, engaging in asynchronous activities that span home, transit, and social spaces (Zhu et al., 2024). This mobility allows learners to access authentic language input in diverse contexts, reinforcing the idea that language learning is embedded in a continuously evolving environment. As a result, the notion

of "learning environment" expands to encompass a distributed network of digital, physical, and social spaces.

The shift toward digital ecologies necessitates a reconsideration of learner agency. In these environments, learners exercise autonomy in selecting tasks, pacing engagement, and interacting with peers or digital agents. Such autonomy is a central feature of contemporary neuro-ecological approaches, which posit that learning outcomes emerge from active participation and adaptation within complex systems (Pinto-Llorente & Izquierdo-Álvarez, 2024). Digital affordances thus function as scaffolds that guide attention, support self-regulation, and facilitate meaningful engagement with linguistic content.

One consequence of these developments is that the digital revolution has blurred the traditional boundaries between formal and informal learning. Learners increasingly encounter language input outside structured classroom settings, through social media, online forums, and immersive games. This shift highlights the active role of the environment in shaping learning trajectories, as learners are required to negotiate meaning and interact with linguistic material in real-time, contextually situated ways (Wang et al., 2022). Such experiences reinforce the perspective that cognitive development is inseparable from environmental interaction.

Moreover, digital learning tools are capable of providing immediate and tailored feedback, which supports neural and cognitive adaptation. The provision of multimodal feedback including textual corrections, auditory reinforcement, and visual cues enhances learners' ability to detect patterns, consolidate memory, and adapt strategies (Zhu et al., 2024). The integration of these features into digital platforms exemplifies how the environment can actively guide learning processes, rather than merely presenting content for passive consumption.

The dynamic nature of digital learning environments also challenges assumptions regarding cognitive load. Learners must navigate multiple streams of input, integrate diverse modalities, and manage interactive tasks simultaneously. While this complexity presents challenges, it also offers opportunities for developing attentional control, working memory capacity, and cognitive flexibility (Britz et al., 2024). In this way, digital environments act as agents that shape not only the content but the structure of cognitive engagement.

Historically, SLA research has emphasized linear progressions from input to comprehension to production. However, the advent of digital environments suggests that learning is more cyclical and adaptive, with feedback loops and interactive affordances facilitating continuous recalibration of understanding. In this sense, digital ecologies embody the principles of complex systems theory, wherein the learner's cognitive development is emergent from interactions with the environment and the technology-mediated affordances it offers (Nguyen & Doan, 2025).

The embodied turn in SLA research further underscores that language acquisition involves sensorimotor engagement. Embodied experiences, such as gestural interaction in virtual reality or multimodal engagement through gamified tasks, enhance the depth of processing and retention (Britz et al., 2024). This perspective shifts attention from purely internal cognitive operations to interactions that integrate body, brain, and environment.

Neuro-ecological research also emphasizes that neural plasticity in adult L2 learners is shaped by the context of learning. Experiences that integrate multimodal input, social interaction, and adaptive feedback promote reorganization in brain networks related to attention, memory, and language processing (Nguyen & Doan, 2025). Digital environments, by providing these integrated affordances, become active agents in facilitating such neural adaptation.

The notion of affordances, central to ecological psychology, provides a framework for understanding the learner-environment interaction in digital SLA. Digital platforms present opportunities for action that learners perceive and act upon, shaping both cognitive strategies

and learning outcomes (Wang et al., 2022). These affordances are not static; they evolve with learner interaction, reflecting the dynamic coupling of cognition and environment.

In addition, the digital revolution facilitates collaborative learning opportunities, allowing learners to co-construct knowledge in interactive spaces. Social feedback, peer interaction, and community engagement enhance motivation and scaffold cognitive development, demonstrating that the environment encompasses not only digital affordances but also social and relational dimensions (Pinto-Llorente & Izquierdo-Álvarez, 2024).

The expanded learning environment also impacts motivation and engagement. Autonomy, immediacy of feedback, and multimodal engagement foster intrinsic motivation, which has been shown to positively influence cognitive and linguistic outcomes (Zhu et al., 2024). Motivation, therefore, is not solely an internal trait but is shaped and mediated by environmental affordances.

Digital ecologies also require learners to develop new skills, including digital literacy, multitasking, and strategic interaction with multimodal content. These skills support cognitive adaptation by enabling learners to navigate complex input streams effectively (Britz et al., 2024). The environment is thus both a site of cognitive challenge and an enabler of growth.

The integration of digital tools and environments into SLA also brings new methodological considerations for research. Longitudinal studies, multimodal data collection, and analysis of learner interaction within digital ecologies are necessary to capture the dynamic interplay between cognition and environment (Nguyen & Doan, 2025). This methodological shift reflects the growing recognition of the environment as an active contributor to learning processes.

The convergence of embodied and neuro-ecological perspectives offers a comprehensive framework for understanding how digital environments influence SLA. By acknowledging that cognition, neural adaptation, and environmental engagement are intertwined, researchers can better conceptualize the mechanisms underlying effective learning in digital contexts (Britz et al., 2024).

Digital learning environments also facilitate personalized learning pathways. Learners can engage with content at their own pace, select tasks aligned with proficiency, and receive feedback that is contingent on their performance. Such personalization reinforces the active role of the environment in shaping cognitive strategies (Zhu et al., 2024).

The social dimension of digital ecologies further enhances learning. Interaction with peers and native speakers via forums, chat platforms, and collaborative tasks allows learners to test hypotheses, negotiate meaning, and refine output, demonstrating the environment's participatory role (Pinto-Llorente & Izquierdo-Álvarez, 2024).

Digital affordances also extend to multimodal input, combining visual, auditory, and textual stimuli. Such integration supports dual coding, deeper encoding, and retrieval processes, demonstrating that environmental features directly influence cognitive mechanisms (Britz et al., 2024).

By facilitating multimodal engagement, immediate feedback, and collaborative opportunities, digital environments enable learners to inhabit complex, interactive ecologies. These ecologies act as co-agents in learning, scaffolding cognitive and neural processes (Nguyen & Doan, 2025).

The continuous availability of digital learning environments allows learners to extend engagement beyond classroom schedules. This temporally distributed learning contributes to consolidation, practice, and adaptation of cognitive strategies over time (Zhu et al., 2024).

Digital ecologies also encourage experimentation and error-based learning. Platforms that provide safe spaces for trial and feedback allow learners to explore linguistic structures actively, reinforcing the environment's role in shaping cognition (Pinto-Llorente & Izquierdo-Álvarez, 2024).

Emerging research also suggests that digital environments can reduce affective barriers, such as anxiety, by offering low-stakes, interactive practice spaces. Reduced anxiety enhances cognitive engagement, showing again how environment and cognition are intertwined (Britz et al., 2024).

The background to this study thus establishes that SLA has been fundamentally transformed by digital technologies, which create environments that are active, adaptive, and multimodal. Learners are now situated within dynamic ecologies where cognition, neural adaptation, and environmental engagement interact continuously.

These developments have motivated a theoretical shift from purely cognitive models to embodied and neuro-ecological frameworks that account for the learner's bodily engagement and interaction with the environment (Nguyen & Doan, 2025). Digital environments provide the context, scaffolding, and affordances that enable these interactions.

Finally, recognizing the environment as an active agent in cognitive development allows researchers and educators to reconceptualize SLA. By situating learners within dynamic, interactive, and multimodal ecologies, this study foregrounds the cognitive-environmental interplay as central to understanding language acquisition in digital contexts (Wang et al., 2022).

1.2 Nature of the Study

This study adopts a critical qualitative literature review approach, emphasizing synthesis, interpretation, and evaluation rather than primary data collection. By integrating findings from cognitive neuroscience, SLA, ecological psychology, and digital pedagogy, the review situates digital second language acquisition (SLA) within a broader interdisciplinary framework. The qualitative nature of the review allows for a nuanced examination of existing theoretical and empirical work, highlighting patterns, contradictions, and gaps in the understanding of how learners interact with complex digital environments. The approach is deliberately critical, not merely descriptive, enabling the study to interrogate assumptions underlying traditional SLA models and to propose a refined conceptualization of learning dynamics in technology-mediated contexts.

The review specifically seeks to interpret, evaluate, and reframe the co-construction of digital SLA by neural, cognitive, and environmental dynamics. Rather than treating cognitive processes or environmental conditions in isolation, the study examines how these elements interact in digital learning ecosystems. For example, multimodal digital tools provide affordances that scaffold cognitive processing, while social and interactive features of the environment shape attentional focus, motivation, and feedback mechanisms. By synthesizing findings across disciplines, the review illuminates the dynamic interplay between learners' neural adaptation, embodied cognition, and the ecological features of digital learning contexts. This integrative perspective foregrounds the learner-environment coupling as a central mechanism in SLA, advancing beyond the linear input-output models that have dominated prior research.

Despite the proliferation of digital technologies in language learning, a gap remains in understanding how cognitive, neural, and environmental factors co-adapt to produce meaningful language outcomes. Existing studies often examine these domains separately, emphasizing either cognitive mechanisms, neural plasticity, or technological affordances, but

rarely considering their interdependence. This fragmentation limits the theoretical and practical insights available for designing effective digital language interventions. The problem, therefore, is not the availability of digital tools but the lack of a coherent, integrative framework that accounts for the neuro-ecological dynamics underlying digital SLA. This review addresses that gap by critically synthesizing existing scholarship and proposing a reframed understanding of how learners, cognition, and digital environments co-construct language acquisition.

1.3 Problem Statement

Despite the widespread adoption of digital technologies in second language acquisition (SLA), there remains a fundamental gap in how research integrates cognitive, neural, and environmental systems to explain learning in these contexts. Much SLA research has focused narrowly on cognitive mechanisms such as working memory, attention, and processing while treating the environment and digital tools as static or peripheral (Klimova & Pikhart, 2023). Simultaneously, investigations into technology-mediated language learning often emphasise tool effectiveness apps, adaptive platforms, virtual reality without critically examining how these tools co-construct neural and cognitive engagement within dynamic digital ecologies (Li & Li, 2023). This fragmentation limits theoretical coherence and leaves unaddressed how digital learning environments mediate cognitive and neural adaptation in SLA.

Furthermore, existing studies typically isolate domains of inquiry either cognitive mechanisms, neural adaptations, or digital learning environments thus neglecting the interdependent nature of what might be called neuro-ecological dynamics. For instance, while neuroplastic changes in adult L2 learners have been documented, such changes are rarely contextualized as functions of environmental affordances and embodied interactions in digital ecologies (Ibáñez et al., 2024). Likewise, digital platforms do more than present content: they structure learner attention, scaffold interaction, offer feedback loops, and shape the affordances for learner action. Without frameworks that recognize how learners, tools, tasks and environments co-adapt, our explanation of digital SLA remains partial and insufficiently grounded.

Moreover, the rapid shift to ubiquitous, anytime-anywhere digital learning has introduced considerable variability and complexity in learning experiences that traditional SLA theories are poorly equipped to capture. Learners now engage in asynchronous, multimodal, socially mediated ecosystems that differ widely in structure, interactivity, access and technological affordances.

 While meta-analyses show promising effects for digital reading and vocabulary acquisition (Zhu, Zhang, & Irwin, 2023), such studies often overlook how individual differences in digital literacy, device access, sociocultural context and environmental quality moderate these outcomes. These ecological and methodological gaps hinder both the generalizability of findings and the practical applicability of research in diverse settings.

Finally, addressing this problem is crucial for advancing both theory and practice in digital SLA. Without an integrated neuro-ecological perspective, educators and researchers risk implementing digital tools and interventions based on fragmented models of learning that emphasizes input or processing while neglecting the active role of environment and interaction. By critically synthesizing theoretical and empirical research across cognitive neuroscience, ecological psychology, digital pedagogy and SLA, this review aims to elucidate how neural, cognitive and environmental factors co-construct language acquisition in digital contexts. In doing so, it strives to inform the design of more effective, evidence-informed digital learning environments that meaningfully harness the interplay of brain, body, environment and technology within second language development.

1.4 Purpose and Objectives

The purpose of this study is to provide a critical, integrative evaluation of neuro-ecological mechanisms in technology-mediated second language acquisition (SLA), bridging cognitive neuroscience, ecological psychology, and digital pedagogy to produce a coherent conceptual understanding of how learners interact with complex digital learning environments. While prior research has examined neural adaptations, cognitive strategies, or digital affordances separately, there is a notable absence of frameworks that account for the dynamic interplay among brain, cognition, and environment in SLA contexts. By synthesizing theoretical and empirical studies, this review seeks to identify dominant paradigms, highlight methodological and conceptual limitations, and uncover patterns of interaction between learners' neurocognitive processes and ecological affordances within digital learning spaces. The objectives are therefore threefold: first, to systematically analyze existing literature on the intersection of neurocognition, ecology, and digital learning in SLA, discerning trends, gaps, and points of convergence; second, to critically evaluate the theoretical orientations that have guided research, noting their explanatory strengths and limitations; and third, to develop a synthesized neuro-ecological model of digital language acquisition that integrates neural, cognitive, and environmental dimensions into a unified conceptual framework. By accomplishing these objectives, the study aims to provide both a theoretically robust and practically relevant lens for understanding and designing technology-mediated language learning environments, ultimately advancing the field beyond isolated cognitive or technological perspectives and fostering a more holistic approach to SLA research.

Research Objectives

Building on the study's purpose, the research is guided by the following objectives:

1. To critically analyze existing literature at the intersection of neurocognition, ecological frameworks, and digital second language acquisition, identifying key trends, gaps, and areas of convergence.
2. To examine dominant theoretical and methodological orientations in the field, highlighting their strengths, limitations, and implications for understanding learner-environment-cognition dynamics.
3. To develop a synthesized neuro-ecological model of technology-mediated SLA that integrates neural, cognitive, and environmental dimensions, offering a coherent conceptual framework for both research and pedagogical practice.

1.5 Research Questions

Aligned with these objectives, the study seeks to answer the following questions:

1. How do neurocognitive and ecological factors interact to shape second language learning in technology-mediated environments?
2. What theoretical perspectives and methodological approaches dominate this interdisciplinary field, and what are their respective limitations?
3. How can insights from neural, cognitive, and environmental research be integrated into a cohesive neuro-ecological framework that informs digital SLA theory and practice?

1.6 Significance of the Study

Theoretical Significance: This study bridges neurocognitive and ecological perspectives in SLA, conceptualizing language learning as a dynamic system where brain, cognition, and environment interact. By integrating these perspectives, it advances theory beyond traditional, compartmentalized models, providing a richer understanding of how learners engage with technology-mediated environments (Nguyen & Doan, 2025; Britz et al., 2024).

Methodological Significance: Methodologically, the study demonstrates the value of a critical qualitative literature review for interdisciplinary synthesis. By evaluating and integrating research across neuroscience, ecology, and digital pedagogy, it identifies theoretical gaps, methodological patterns, and points of convergence, offering a rigorous model for future integrative SLA research (Zhu, Zhang, & Irwin, 2024).

Practical Significance: Practically, the study informs digital language pedagogy by translating neuro-ecological insights into actionable strategies. Digital learning environments can be designed to align w ith neural and cognitive processes through multimodal input, adaptive feedback, and interactive affordances, enhancing engagement, motivation, and overall learning outcomes (Pinto-Llorente & Izquierdo-Álvarez, 2024; Wang, Zhang, & Long, 2022).

2. THEORETICAL AND CONCEPTUAL FRAMEWORK

2.1 Neuro-ecological Theory of Learning

The neuro-ecological theory of learning provides a contemporary framework for understanding second language acquisition (SLA) as a dynamic interplay among brain, body, and environment. Rooted in principles of embodied cognition and ecological psychology, neuro-ecology posits that learning does not occur solely in the brain but emerges through interactions between neural processes, sensorimotor activity, and environmental affordances (Gibson, 1979; Britz et al., 2024). In this framework, the environment is not a passive backdrop but an active participant, offering cues, constraints, and opportunities that shape cognitive and neural adaptation. Such a perspective contrasts with traditional cognitive models that treat the mind as an isolated processor of input, instead emphasizing coupling and continuous co-adaptation between learner and environment.

Central to neuro-ecological theory is the concept of brain–body–environment coupling, which posits that cognition emerges through the integration of neural activity, bodily action, and environmental interaction. In digital SLA contexts, this principle highlights how multimodal learning tools such as interactive apps, virtual reality, and gesture-based interfaces mediate embodied interactions that directly influence neural and cognitive processes. For instance, evidence from neuroimaging and eye-tracking studies shows that sensorimotor engagement during digital language tasks enhances memory consolidation and syntactic processing (Gkintoni, Vassilopoulos, & Nikolaou, 2025). This coupling underscores that environmental design and affordances are not peripheral but integral to shaping the learning trajectory, particularly in technology-mediated SLA.

Another key principle is adaptation, which frames learning as a continuous process of neural and behavioral adjustment to environmental conditions. Neuro-ecological theory posits that exposure to enriched, interactive environments can accelerate synaptic plasticity and strengthen functional neural connectivity, particularly in language-related networks such as the inferior frontal gyrus, dorsal anterior cingulate cortex, and superior temporal gyrus (Ibáñez et al., 2024). In digital contexts, adaptation is shaped not only by the nature of linguistic input but also by features such as immediate feedback, interactivity, and multimodal representation. Critically, adaptation is individualized, meaning that learners' prior experience, cognitive control, and motivation interact with environmental affordances to produce differential outcomes a principle central to understanding variability in digital SLA success.

Dynamic systems thinking further informs neuro-ecological approaches by conceptualizing learning as emergent, nonlinear, and context-dependent. According to this perspective, SLA is the product of complex interactions among multiple subsystems including cognitive, neural, emotional, and social factors operating over time within digital and physical environments (Larsen-Freeman & Cameron, 2008; Britz et al., 2024). Digital tools introduce additional layers

of complexity, offering dynamic affordances that can change in real-time based on learner input or system adaptation. By applying dynamic systems thinking, researchers can model SLA as a temporally unfolding process, capturing fluctuations in performance, motivation, and cognitive load as learners navigate technologically mediated ecologies.

Finally, the neuro-ecological framework provides a conceptual bridge linking theory, empirical evidence, and pedagogical practice. By foregrounding the interdependence of brain, body, and environment, it allows scholars and educators to move beyond fragmented approaches that isolate cognitive processes or digital tools. Instead, it emphasizes integrative design principles: learning environments should support embodied engagement, provide meaningful affordances, and adapt to learners' cognitive and neural states. In doing so, neuro-ecology offers a robust theoretical foundation for understanding and optimizing digital SLA, ensuring that research and practice account for the full spectrum of dynamic, co-constructed learning processes (Britz et al., 2024; Gkintoni et al., 2025).

2.2 Cognitive Neuroscience of SLA

Cognitive neuroscience has substantially advanced our understanding of second language acquisition (SLA) by mapping the neural correlates of language processing and bilingualism. Research consistently implicates the left inferior frontal gyrus (Broca's area), superior temporal gyrus (Wernicke's area), and dorsolateral prefrontal cortex in the comprehension and production of L2, highlighting both shared and distinct networks relative to the first language (L1) (Abutalebi & Green, 2016; Gkintoni, Vassilopoulos, & Nikolaou, 2025). Bilingual studies further reveal that neural activation patterns depend on proficiency, age of acquisition, and context of use, with highly proficient learners exhibiting overlapping L1 and L2 activations, whereas late learners show more distributed activation and greater recruitment of domain-general executive regions (Li et al., 2015). Such findings emphasize that neural organization in SLA is dynamic, context-dependent, and sensitive to individual differences, offering insight into the mechanisms underlying variability in digital learning environments.

Attention and working memory are central cognitive systems in SLA, shaping how learners perceive, encode, and retrieve linguistic input. Neuroimaging studies demonstrate that sustained attention engages the anterior cingulate cortex and parietal networks, facilitating the selection and inhibition of competing linguistic representations in bilingual processing (Grundy et al., 2017). Working memory, particularly verbal working memory, underpins sentence comprehension, vocabulary acquisition, and syntax integration, linking prefrontal and parietal regions. In technology-mediated SLA, the interaction between attentional control and working memory is critical: digital platforms present multimodal input streams, such as simultaneous visual and auditory stimuli, requiring learners to integrate information across modalities (Pérez-Serrano et al., 2022). Consequently, attentional engagement and memory load management become essential for effective learning in digital contexts, suggesting that cognitive neuroscience provides a foundational explanation for why certain digital affordances facilitate or hinder SLA.

Neuroplasticity the brain's capacity to reorganize structurally and functionally in response to experience is a core principle in understanding L2 learning. Longitudinal neuroimaging research demonstrates that intensive L2 instruction leads to structural changes in grey matter density in regions such as the left inferior parietal lobule and anterior cingulate cortex, as well as increased functional connectivity in language control networks (Hervais-Adelman et al., 2018; Li et al., 2015). Critically, neuroplastic adaptation is modulated by exposure frequency, task complexity, and age of acquisition. In digital SLA, multimodal engagement where learners simultaneously process text, audio, visual cues, and interactive feedback may amplify plastic

changes by recruiting multiple sensory and cognitive pathways, fostering stronger memory consolidation and deeper syntactic-semantic integration (Gkintoni et al., 2025). This underscores the potential of technology-mediated environments to harness neuroplastic mechanisms for enhanced language learning outcomes.

Multimodal engagement in SLA leverages the integration of sensory modalities to reinforce neural encoding and cognitive processing. For example, studies combining gesture with speech in L2 vocabulary learning show enhanced retention and retrieval compared to unimodal input, with fMRI evidence indicating co-activation of motor, visual, and language areas (Skipper et al., 2017). Similarly, digital VR and gamified tasks offer rich multimodal contexts that stimulate embodied cognition, connecting perception, action, and linguistic representations in a dynamic network (Britz et al., 2024). These findings illustrate that multimodal experiences are not merely supplementary; they are integral to shaping neural circuits that support language learning, providing a bridge between cognitive neuroscience and ecological principles in digital SLA.

Finally, integrating cognitive neuroscience with neuroecological perspectives provides a robust framework for understanding SLA in technology-mediated environments. Neural correlates of attention, memory, and language processing interact continuously with environmental affordances and embodied engagement to co-construct learning trajectories. For instance, digital platforms that provide adaptive, interactive, and multimodal feedback create a scaffolded environment that aligns with learners' neural processing capacities, supporting both immediate performance and long-term neuroplastic adaptation (Pérez-Serrano et al., 2022; Britz et al., 2024). This integration demonstrates that understanding SLA requires moving beyond isolated neural or cognitive mechanisms to consider the dynamic, reciprocal interaction between brain, cognition, and environment, aligning with the broader neuro-ecological model of digital language learning.

2.3 Ecological and Digital Learning

Ecological psychology frames learning as an emergent process shaped by perception-action coupling, where learners continuously interact with the affordances provided by their environment (Gibson, 1979; van Lier, 2004). In second language acquisition (SLA), this perspective suggests that the learner does not passively absorb input but actively perceives, selects, and exploits environmental cues to scaffold understanding and production of the target language. Cognitive and neural processes are embedded within these interactions, such that attention, memory, and problem-solving capacities are activated and shaped by environmental affordances. Ecological models thus challenge traditional classroom-centric approaches, emphasizing that language learning emerges from dynamic, context-sensitive engagements rather than from isolated cognitive processes (van Lier, 2004; Wang et al., 2022).

Socio-cognitive perspectives complement ecological psychology by highlighting the role of social interaction, collaboration, and mediated learning in shaping cognitive development. Vygotskian principles such as the Zone of Proximal Development (ZPD) and scaffolding are particularly relevant in digital contexts, where learners can receive guidance from teachers, peers, or intelligent tutoring systems in real time (Pérez-Serrano et al., 2022). In digital learning ecosystems, these socio-cognitive processes are extended across time and space, allowing asynchronous and synchronous interactions that maintain the social and cognitive scaffolding necessary for sustained learning. Such environments exemplify how socio-cognitive principles operate within affordance-rich digital ecologies, where learners' agency, collaboration, and problem-solving are dynamically supported (Onodipe et al., 2023).

Digital environments themselves can be conceptualized as cognitive ecosystems, offering multimodal, interactive, and adaptive affordances that scaffold L2 learning. For example, virtual reality, language apps, and gamified learning platforms combine audio, visual, and gestural input to promote embodied cognition and sensorimotor engagement, which support memory, attention, and comprehension (Britz et al., 2024). Studies show that learners in these environments demonstrate higher retention and greater engagement compared to traditional instruction, particularly when multimodal cues are aligned with cognitive load principles (Zhu et al., 2024). Such findings underscore that digital platforms are not neutral channels for content delivery; they actively shape perception, cognition, and neural adaptation, functioning as extended environments in which language learning unfolds.

A critical aspect of ecological and digital perspectives is the interaction between learner, environment, and technology, which is reciprocal and context-dependent. Environmental affordances in digital SLA, such as real-time feedback, adaptive difficulty, and multimodal scaffolds, dynamically influence learners' attention, motivation, and cognitive processing (Wang et al., 2022; Onodipe et al., 2023). Conversely, learners' prior knowledge, goals, and engagement patterns shape how they perceive and utilize these affordances. This bidirectional coupling aligns closely with neuro-ecological principles, where cognition and neural adaptation are co-constructed by interaction with richly structured, multimodal environments. The implication is that successful digital SLA interventions must consider the alignment of cognitive, social, and ecological factors rather than focusing solely on instructional content or technology features.

Finally, integrating ecological psychology, socio-cognitive theory, and digital learning perspectives provides a comprehensive framework for understanding technology-mediated SLA as an ecosystemic process. Learning emerges through continuous cycles of perception, action, feedback, and adaptation, where multimodal affordances, social interaction, and learner agency are intertwined. This perspective highlights the importance of designing digital environments that support embodied engagement, multimodal input, adaptive scaffolding, and social interaction, all of which collectively enhance learning outcomes (Britz et al., 2024; Pérez-Serrano et al., 2022; Zhu et al., 2024). By conceptualizing digital SLA environments as cognitive ecologies, this framework bridges theory, empirical evidence, and pedagogy, offering practical guidance for both researchers and instructional designers seeking to optimize learning in digital contexts.

2.4 Technology-Mediated Language Learning

Digital platforms are increasingly conceptualized as ecological extensions of the learner's cognitive environment, mediating processes such as attention, memory, and problem-solving in ways that traditional classrooms cannot. By embedding language learning within interactive, multimodal contexts, these technologies extend the boundaries of cognition beyond the individual mind. A systematic review of empirical studies suggests that technology supports more efficient input, richer interaction, and timely feedback in language learning settings (Noori, 2025).

Interactivity, immersion, and immediate feedback emerge as key digital affordances that shape neural engagement. Interactive tasks encourage active manipulation of language input, immersive environments provide rich contextual cues, and instant feedback supports rapid error-correction and reinforcement. Research on technology-mediated task-based language teaching (TBLT) demonstrates how digital tasks facilitate meaningful language use and scaffold interaction, enhancing learning opportunities (Chong & Reinders, 2020; Smith & González-Lloret, 2021).

For Technology-Mediated Language Learning (TMLL) to be truly effective, teachers must possess strong ICT skills as well as high levels of emotional and social intelligence. The integration of technology into language learning environments requires educators who can confidently navigate digital tools while fostering supportive, empathetic, and interactive classroom dynamics. This balance ensures that technology enhances, rather than replaces, the human element of teaching. Therefore, a teacher who is both technologically competent and emotionally intelligent remains an indispensable and irreplaceable component of successful technology-mediated language instruction (Langat, 2005).

However, critical debates emphasize that technology alone does not guarantee effective learning: pedagogical design, learner agency, and social interaction remain central determinants of outcomes. Empirical evidence shows that while technology can reduce foreign-language anxiety through personalized feedback and safe interaction spaces, it may also exacerbate anxiety through cognitive overload or reduced human connection (Noori, 2025). Thus, technology-mediated language learning is most effective when integrated thoughtfully to complement not replace human guidance, reflection, and social practice.

2.5 Integrative Conceptual Model

The proposed neuro-ecological framework for digital second language acquisition (SLA) synthesizes insights from cognitive neuroscience, neuroplasticity, ecological psychology, and digital learning research to provide a comprehensive conceptual model. At its core, the framework posits that learning emerges through continuous interaction among neural systems, cognitive mechanisms, and environmental affordances, which are dynamically coupled and co-adaptive. Neural systems including regions responsible for language processing, working memory, attention, and executive control interact with cognitive mechanisms such as attention allocation, memory encoding, and sensorimotor integration to facilitate L2 acquisition (Abutalebi & Green, 2016; Gkintoni, Vassilopoulos, & Nikolaou, 2025). These internal processes are reciprocally influenced by external affordances present in digital learning environments, including multimodal input, interactive feedback, scaffolding, and collaborative opportunities (Britz et al., 2024; Pérez-Serrano et al., 2022).

A key feature of the framework is its focus on feedback loops and co-adaptation. Learners' cognitive engagement with environmental affordances modifies neural activation patterns and supports neuroplastic adaptation over time, which in turn shapes subsequent interaction with the environment. For example, repeated exposure to multimodal digital input (text, audio, visual, gestural cues) strengthens the integration of perceptual and linguistic networks, enhancing memory consolidation and language fluency (Skipper et al., 2017; Valentin-Rivera & Yang, 2021). At the same time, digital platforms adapt to learner performance by providing tailored tasks and scaffolds, creating a bidirectional flow of influence where learner behavior reshapes environmental affordances while neural and cognitive changes modulate perception and engagement.

The framework also emphasizes the role of individual differences and context in shaping the neuro-ecological dynamics of digital SLA. Age of acquisition, proficiency, working memory, motivation, and digital literacy influence how learners perceive, exploit, and adapt to environmental affordances, thereby moderating neural and cognitive outcomes (Li, Legault, & Litcofsky, 2015; Britz et al., 2024). Similarly, the characteristics of the digital learning environment—such as affordance richness, interactivity, and multimodality—determine the quality and frequency of learner-environment interactions. By integrating these factors, the model captures both generalizable mechanisms of digital SLA and the variability inherent in individual learning trajectories.

From a practical perspective, this neuro-ecological model offers actionable implications for the design of digital SLA environments. Educators and instructional designers can leverage multimodal affordances, adaptive feedback, and collaborative tools to align digital learning experiences with learners' neural and cognitive capacities. For instance, scaffolding that engages sensorimotor systems—such as interactive drag-and-drop exercises, speech recognition tasks, or VR role-playing simulations—can accelerate neuroplastic adaptation while maintaining cognitive load within optimal ranges (Britz et al., 2024; Zhu et al., 2024). By embedding these principles, digital platforms can facilitate co-adaptive learning pathways, enhancing both short-term performance and long-term proficiency.

Finally, a diagrammatic representation of the framework visually illustrates the interplay between neural, cognitive, and environmental components. The model depicts learners at the center, engaging in continuous loops of perception, action, and feedback with environmental affordances, which modulate neural activation and cognitive processing. Arrows indicate bidirectional influence: learner behavior influences the environment, while environmental affordances shape neural and cognitive adaptation. This representation reinforces the dynamic, emergent nature of digital SLA, emphasizing that learning is not linear but arises from the co-adaptive interaction of multiple systems over time. In this way, the framework bridges theory, empirical evidence, and practical application, offering a robust foundation for future research and pedagogical innovation in digital language learning contexts.

Langat, A. C. (2025). Integrative conceptual model.
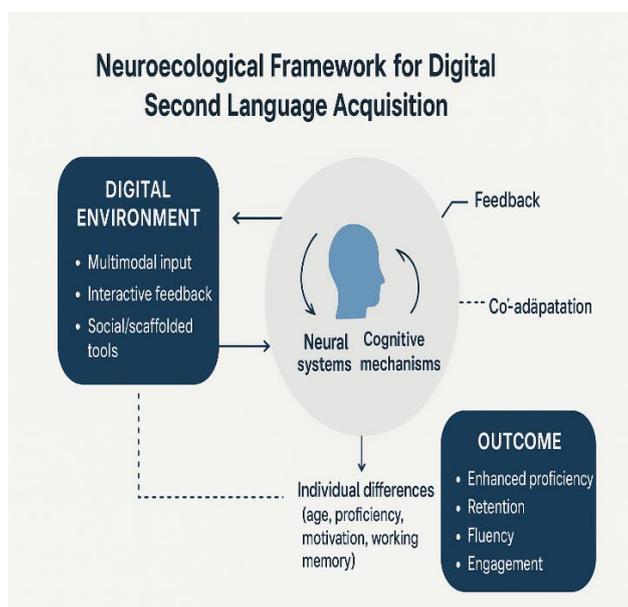
3.METHODOLOGY
3.1 Design: Qualitative Critical Interpretive Synthesis (CIS) Approach
This study adopts a qualitative Critical Interpretive Synthesis (CIS) methodology, which emphasizes iterative, interpretive engagement with literature rather than aggregative summarization. Unlike systematic reviews or meta-analyses, which primarily quantify effects, a critical review emphasizes conceptual integration, theoretical critique, and identification of knowledge gaps (Grant & Booth, 2009; Ferrari, 2015). This approach is particularly suitable for exploring the complex interplay of cognitive, neural, and environmental factors in

technology-mediated learning, allowing for the development of an integrative conceptual framework.

Unlike conventional systematic reviews, CIS prioritizes conceptual coherence, allowing the integration of diverse empirical and theoretical sources into a unified interpretive framework. The approach facilitates identification of underlying assumptions, theoretical tensions, and emergent patterns across studies, producing insights that extend beyond descriptive summaries. Central to CIS is its focus on theoretical contribution. Through interpretive coding and constant comparison, the synthesis develops higher-order constructs that illuminate the relationships between digital affordances, cognitive engagement, and language learning outcomes. This allows the study to critically examine not only what technologies do in language learning but also how and why they shape cognitive and pedagogical processes, situating findings within broader learning theory.

Critical evaluation underpins the CIS approach, requiring rigorous interrogation of methodological quality, epistemological assumptions, and contextual relevance of included studies. By combining conceptual synthesis with reflexive critique, CIS produces nuanced insights into both evidence and its limitations, ensuring that theoretical contributions are robust, credible, and applicable to future research and practice in technology-mediated language learning.

3.2 Data Sources and Selection Criteria

The review draws upon peer-reviewed journal articles, book chapters, and high-impact empirical studies published between 2015 and 2025. Databases consulted include Web of Science, Scopus, PubMed, ERIC, and Google Scholar. Inclusion criteria were: (1) studies focusing on digital or technology-mediated second language learning, (2) research integrating cognitive, neural, or ecological perspectives, and (3) empirical, theoretical, or conceptual works offering insights into neuro-ecological processes. Studies addressing unrelated cognitive domains or non-digital SLA contexts were excluded to maintain focus and relevance.

Inclusion criteria required studies to explicitly address the intersection of neurocognition, ecological perspectives, and digital language learning, ensuring relevance to both theoretical and empirical dimensions of technology-mediated SLA. Only studies providing conceptual frameworks, mechanistic insights, or analytical discussion were included, prioritizing contributions to theoretical understanding over mere descriptive reporting.

Exclusion criteria eliminated purely descriptive studies lacking theoretical grounding or critical evaluation, as well as publications outside peer-reviewed outlets or unrelated disciplinary contexts. This strategy ensured that the synthesis remained focused on studies capable of supporting conceptual coherence, theoretical contribution, and critical interpretation, consistent with the Critical Interpretive Synthesis (CIS) approach.

3.3 Data Extraction, Synthesis and Analytical Procedures

Key information extracted from each source included study objectives, theoretical framework, methodology, findings, and relevance to neuro-ecological SLA models. Thematic synthesis was employed to identify patterns, relationships, and contradictions across studies, allowing for critical evaluation of dominant theoretical perspectives, methodological strengths and weaknesses, and emergent conceptual frameworks (Thomas & Harden, 2008). Particular attention was given to how digital affordances, learner cognition, and neural adaptation interact, highlighting points of convergence and divergence across the literature.

The analytical process followed a thematic synthesis approach, beginning with iterative coding of included studies for key conceptual categories: neural, cognitive, environmental, and

technological dimensions of language learning. This coding process enabled the identification of recurring patterns, relationships, and divergences across studies, forming the foundation for higher-order interpretation.

A critical appraisal was conducted in parallel, evaluating each study's theoretical coherence, methodological rigor, and relevance to the research questions. This step ensured that findings were not only descriptively aggregated but also critically interrogated, highlighting the robustness, limitations, and potential biases of the evidence base.

Finally, an interpretive integration synthesized these insights into higher-order themes, producing a conceptual framework that links neural engagement, cognitive processes, ecological context, and digital affordances in technology-mediated language learning. This process generated a nuanced, theoretically informed understanding that extends beyond individual studies, consistent with the goals of a Critical Interpretive Synthesis.

3.4 Rigor, Validity, Trustworthiness and Reflexivity

To maintain rigor, the review followed established principles for qualitative literature syntheses, including transparent selection criteria, systematic extraction of data, and critical appraisal of methodological quality and theoretical coherence (Finfgeld-Connett, 2018). Triangulation across multiple disciplines (neuroscience, ecology, SLA, and digital pedagogy) enhanced the credibility and comprehensiveness of the synthesis.

Trustworthiness in this synthesis was established through transparent reporting of inclusion and exclusion criteria, systematic database searches, and documentation of the study selection process. By explicitly outlining these criteria, the study ensures reproducibility and allows readers to evaluate the scope and boundaries of the evidence considered.

Reflexivity was embedded throughout the research process, with critical acknowledgment of the interpretive stance, theoretical orientation, and potential biases influencing coding, appraisal, and synthesis. The researcher's engagement with both ecological and neurocognitive frameworks shaped interpretation of findings, highlighting the importance of reflective practice in qualitative synthesis and ensuring that conclusions are presented with awareness of their epistemological and conceptual foundations.

3.5 Ethical Considerations

As a literature-based study, this research does not involve human participants and therefore presents no direct ethical risks. Nonetheless, ethical rigor was carefully maintained throughout the study to ensure the integrity and credibility of the synthesis. This involved accurately representing the findings, interpretations, and theoretical contributions of all included studies, avoiding misrepresentation or selective reporting that could distort the evidence base.

Proper attribution of ideas and findings was rigorously applied, with all sources cited in accordance with APA 7th edition guidelines, demonstrating respect for intellectual property and scholarly norms. Additionally, reflexivity was embedded in the interpretive process to acknowledge how the researcher's theoretical orientation, prior knowledge, and interpretive stance may have influenced coding, critical appraisal, and synthesis of the literature.

Finally, transparency, methodological reporting including database selection, inclusion/exclusion criteria, and analytical procedures further reinforces the ethical conduct of this research. By adhering to these standards, the study ensures that the synthesis is trustworthy, accountable, and replicable, providing a robust foundation for future research and practical applications in technology-mediated language learning.

4. LITERATURE REVIEW

This section constitutes the core of the study, providing a critical, integrative, and theoretically informed synthesis of current research at the intersection of neurocognition, ecological theory, and digital second language acquisition (SLA). The review moves beyond descriptive summaries, aiming to identify underlying mechanisms, conceptual tensions, and emergent patterns that illuminate the cognitive environmental interplay in technology-mediated language learning.

Guided by a Critical Interpretive Synthesis (CIS) approach, the literature review prioritizes conceptual coherence and theoretical contribution. It examines how digital affordances such as interactivity, immersion, and feedback interact with neural and cognitive processes within ecologically situated learning contexts. By critically appraising methodological rigor, theoretical grounding, and contextual relevance, this review identifies not only what is known about technology-mediated SLA but also where gaps and opportunities for further research remain.

Ultimately, this section seeks to develop a cohesive conceptual framework linking neurocognitive engagement, ecological dynamics, and digital tools, offering insights that extend beyond individual studies. The synthesis provides a foundation for understanding how cognitive processes are distributed across learners, tasks, and technological environments, highlighting implications for both theory and practice in contemporary SLA research.

4.1 Theoretical Foundations: Krashen's Input Models and ICT Integration

Stephen Krashen's (1982) theory of second language acquisition (SLA) provides a foundational framework for understanding how learners internalize language through meaningful exposure rather than through explicit instruction. His six interrelated hypotheses— the Acquisition–Learning Hypothesis, Monitor Hypothesis, Natural Order Hypothesis, Input Hypothesis, Affective Filter Hypothesis, and Compelling Input Hypothesis—collectively position language acquisition as a subconscious, input-driven process influenced by emotional, cognitive, and environmental variables. Within this framework, language learning is optimized when learners are exposed to comprehensible and engaging input in low-anxiety contexts that stimulate natural acquisition rather than mechanical learning. However, Krashen's models, while revolutionary in their emphasis on affective and input-based factors, predate the digital revolution and therefore require reinterpretation in light of contemporary technological affordances that have transformed how linguistic input is accessed, processed, and internalized. According to Langat (2005), integrating Information and Communication Technologies (ICTs) into Krashen's theoretical framework—across all ecological spheres of SLA, including the ecology of Special Needs Education (SNE)—significantly enhances both its explanatory power and practical relevance. By embedding language learning within multimodal, interactive, and ecologically dynamic environments, ICT transforms Krashen's input-based model into a more inclusive and adaptive system. Digital tools such as adaptive language software, multimedia resources, and virtual learning platforms provide learners with personalized exposure to comprehensible input, thereby concretizing Krashen's Input and Compelling Input Hypotheses within digital contexts. Furthermore, ICT-based environments align with the Affective Filter Hypothesis by lowering anxiety and fostering intrinsic motivation through gamified tasks, collaborative virtual spaces, and flexible, self-paced learning opportunities. Within SNE contexts, ICT integration introduces crucial affordances—such as text-to-speech programs, visual scaffolding, and assistive interfaces—that enhance accessibility, engagement, and autonomy for diverse learners. Collectively, these affordances extend Krashen's original propositions into inclusive, neuro-ecological domains, where linguistic input becomes

multisensory, adaptive, and cognitively enriching, redefining language acquisition as a holistic process grounded in both human and technological interactivity.

From a neuro-ecological standpoint, ICT tools function as external cognitive scaffolds that interact with neural mechanisms of attention, memory, and motivation. The integration of Krashen's input-based model with neurocognitive and ecological theory suggests that digital affordances stimulate the same neural pathways responsible for language comprehension and consolidation, while embedding learning within socially and environmentally distributed systems. This convergence reframes Krashen's hypotheses as components of a broader cognitive–environmental ecosystem in which linguistic input, neural adaptation, and technological mediation co-construct the learning process. Consequently, ICT-enhanced models of SLA reaffirm the enduring relevance of Krashen's principles while extending them to encompass embodied interaction, environmental feedback, and neuroplastic engagement within digital learning ecologies.

Despite their lasting influence, early cognitive theories of language learning were critiqued for overlooking the interactive and environmental dimensions of cognition. Traditional perspectives assumed that mental representations developed independently of context, thereby neglecting the roles of perception, attention, and social interaction in shaping learning. By the 1990s, advances in cognitive neuroscience supported by innovations in brain imaging technologies such as functional magnetic resonance imaging (fMRI) and electroencephalography (EEG)—catalyzed a paradigm shift toward empirically grounded studies of bilingual processing and neural adaptation. Research revealed that second-language acquisition engages dynamically adaptive neural networks involving the prefrontal cortex, temporal lobes, and subcortical structures (Abutalebi & Green, 2007). Further evidence of neural plasticity demonstrated that proficiency and exposure reshape cortical representations, highlighting that language learning is not a fixed cognitive capacity but a biologically adaptable process (Li et al., 2014).

However, purely neurocognitive approaches faced limitations in isolating brain processes from the learner's lived environment. While these models illuminated where and how neural activation occurs, they often neglected why such activation is socially and contextually mediated. Critics such as van Lier (2004) argued that focusing exclusively on neural correlates reduces language learning to internal processes, thereby ignoring affective, cultural, and interactive dimensions of experience. This critique prompted a shift toward integrative frameworks recognizing that cognition is situated, embodied, and distributed across neural, bodily, and environmental systems. The embodied cognition paradigm advanced this reorientation by asserting that cognitive processes are grounded in sensory–motor activity. From this perspective, language learning involves not merely symbolic manipulation but active engagement with multimodal stimuli, gestures, and spatial contexts (Barsalou, 2008). Embodied approaches thus bridge neurocognitive evidence with ecological theory by redefining linguistic meaning as emerging through perception and action within authentic environments.

Parallel to the embodied turn, ecological perspectives inspired by Gibson's (1979) theory of affordances introduced a dynamic system view of SLA. Scholars such as van Lier (2004) and Larsen-Freeman and Cameron (2008) emphasized that language development unfolds through adaptive interactions between learners and their environments. Cognition, therefore, is not confined to the individual but distributed across social, material, and technological networks. This ecological lens reframes language learning as participation in complex adaptive systems where environmental affordances, technological mediation, and social feedback co-constitute development. The convergence of neurocognitive, embodied, and ecological paradigms has

given rise to a neuro-ecological perspective on SLA, which positions language learning as both biologically grounded and environmentally embedded—a dynamic process wherein neural adaptation interacts continuously with social, technological, and ecological structures. Recent research increasingly integrates neuroscientific insights with ecological design principles to explain how digital environments shape attention, motivation, and language processing (Davis & Sumara, 2006; Li, 2022). This conceptual evolution marks a decisive shift from viewing language learning as isolated mental computation to understanding it as an integrated cognitive–environmental phenomenon, establishing a robust foundation for examining ICT-mediated language acquisition in the digital age.

Conception diagram of Langat and Krashen (2025)
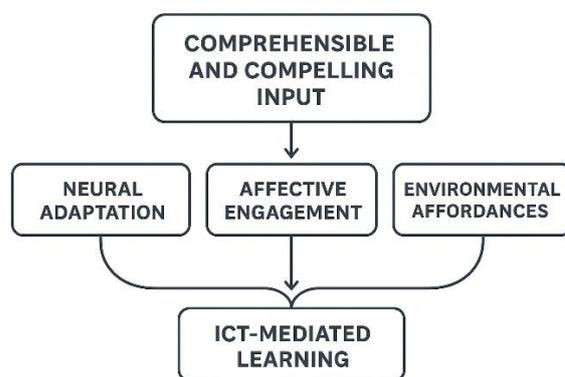
4.2 Neurocognitive Dimensions of Second Language Acquisition

Research into the neurocognitive foundations of second language acquisition (SLA) has illuminated how language processing is distributed across interconnected neural networks rather than confined to isolated cortical regions. Classical language areas such as Broca's and Wernicke's regions remain central to syntactic and semantic processing, yet more recent imaging studies reveal extensive engagement of the prefrontal cortex, anterior cingulate cortex, and parietal regions during second-language (L2) comprehension and production (Perani & Abutalebi, 2005; Kroll & Bialystok, 2013). This expanded activation reflects the cognitive control and attentional demands inherent in managing multiple linguistic systems, suggesting that L2 processing involves both shared and distinct neural mechanisms relative to first-language use.

A substantial body of evidence underscores the role of attention and working memory in modulating neural activation during L2 tasks. Controlled attention enables learners to inhibit interference from their dominant language, while working memory supports the manipulation of novel lexical and syntactic information (Baddeley, 2012; Linck, Osthus, Koeth, & Bunting, 2014). Functional connectivity analyses indicate that higher-proficiency bilinguals display more efficient coordination between executive control networks and language-specific regions, reflecting greater automatization of processing (Abutalebi & Green, 2016). These findings link neurocognitive adaptability with linguistic experience and attentional regulation.

Another critical mechanism is memory consolidation, particularly the integration of linguistic representations during sleep-related neural replay. Studies employing event-related potentials (ERPs) demonstrate that sleep enhances the stabilization of newly learned words and grammatical structures through hippocampal–neocortical interactions (Durrant, Cairney, & Lewis, 2013). Such evidence connects the micro-dynamics of neural oscillation to macro-level

outcomes in vocabulary retention and syntactic acquisition, reinforcing the biological basis of SLA processes.

The contribution of multimodal input has also gained attention within neurocognitive research. Multisensory integration linking auditory, visual, and motor cues has been shown to enhance neural activation patterns and improve comprehension and recall (Mayer et al., 2015). This aligns with embodied perspectives suggesting that language learning engages perception–action systems, integrating sensory experience into cognitive representation. The implication is that digital platforms offering interactive, multimodal input may simulate the sensory richness necessary for robust neural engagement in SLA.

Perhaps the most compelling neurocognitive finding in recent decades concerns neuroplasticity in adult language learners. Structural and functional imaging reveals that intensive language training induces measurable cortical reorganization, including increased gray-matter density in the inferior parietal lobule and enhanced white-matter integrity in language-related tracts (Li, Legault, & Litcofsky, 2014; Martensson et al., 2012). These changes demonstrate that adult brains retain the capacity for significant adaptation, challenging earlier notions of critical-period constraints and highlighting the brain's responsiveness to linguistic and environmental input.

Despite these advances, the neurocognitive tradition has faced methodological and conceptual critique. Much of the evidence derives from highly controlled laboratory experiments that isolate linguistic stimuli from authentic communicative or ecological contexts (van Lier, 2004; Ellis, 2019). Such reductionist designs risk oversimplifying the complex, socially mediated nature of language learning, thereby limiting ecological validity. While they reveal neural correlates of specific processes, they often fail to account for how contextual, emotional, and technological environments shape neural engagement.

Consequently, contemporary scholarship argues for an integrative neuro-ecological perspective, combining neuroscientific precision with ecological authenticity. This approach situates neural activation within the lived dynamics of learning acknowledging that attention, memory, and plasticity are not only neurobiological phenomena but also environmentally distributed processes influenced by interaction, context, and digital mediation. Bridging neurocognitive evidence with ecological theory thus offers a more comprehensive account of how brains learn languages in complex, technology-rich environments.

4.3 Ecological and Socio-cognitive Dimensions

The ecological and socio-cognitive turn in second language acquisition (SLA) reframed learning as an emergent, dynamic process that unfolds through continuous interaction between the learner and the environment. Drawing on Gibson's (1979) theory of affordances and Vygotskian sociocultural principles, this perspective views language not as a static system to be internalized but as a tool for participation within situated activities. Learners engage with linguistic input, peers, and digital artifacts in ways that mutually shape cognition and context. In contrast to traditional information-processing models, ecological frameworks emphasize that cognition is situated, embodied, and distributed across social, material, and technological networks (Lantolf & Thorne, 2006; van Lier, 2004).

Affordances the action possibilities offered by the environment play a central role in ecological accounts of SLA. In technology-mediated learning, affordances arise from interactive interfaces, multimodal feedback, and social networking tools that enable learners to act meaningfully within digital spaces (Blin, 2016). For example, virtual environments and intelligent tutoring systems afford opportunities for experimentation, self-expression, and

authentic communication. Such affordances shape the learner's attentional and motivational dynamics, influencing how input becomes intake and how meaning is co-constructed in interaction.

Closely related is the principle of situated learning, which posits that knowledge develops through participation in socially meaningful practices (Lave & Wenger, 1991). Within digital contexts, situated engagement occurs through collaborative platforms, online gaming, and immersive simulations where language is used for real purposes. Empirical studies show that these environments foster agency, identity formation, and adaptive problem-solving (Reinhardt & Thorne, 2020). This suggests that digital contexts are not merely delivery mechanisms for input but integral components of the learning ecology that mediate cognition and social participation.

The concept of distributed cognition further advances ecological thinking by recognizing that cognitive activity extends beyond the individual to include tools, artifacts, and communicative systems (Hutchins, 1995). In technology-mediated SLA, distributed cognition manifests in the interplay between human and digital agents such as when learners co-construct meaning with AI-based feedback systems or collaboratively edit texts using shared digital tools. This distributed framework highlights how language learning emerges from coordinated activity among participants and technologies rather than from isolated mental computation.

Context, feedback, and social participation are thus seen as constitutive not supplementary components of language development. Interactionist research has long emphasized the role of corrective feedback and negotiation of meaning (Long, 1996), but ecological approaches extend this by situating feedback within multimodal, reciprocal systems. In digital environments, feedback occurs through a blend of algorithmic prompts, peer responses, and environmental cues, producing complex feedback ecologies that enhance attention and self-regulation (Li, 2022).

It is also important to note that while ecological role is crucial in enhancing SLA, the role of a teacher is very vital. Langat (2025) discusses that while Information and Communication Technology (ICT) has transformed the educational landscape by improving access to resources, enabling interactive learning, and promoting student-centered instruction, it should be viewed as a supportive tool rather than a substitute for teachers. The article emphasizes that technology can enhance efficiency and engagement in the classroom, but it lacks the emotional intelligence, ethical judgment, and personal connection that teachers provide. Andrew further argues that the effectiveness of ICT depends on how well educators integrate it into their teaching strategies to complement, not replace, human interaction. Ultimately, the paper concludes that a balanced approach where technology and teachers work hand in hand is essential to achieving meaningful and holistic learning outcomes.

Despite their conceptual richness, ecological and embodied models face persistent critique. While they capture the social and contextual dynamics of learning, they often lack neural evidence and mechanistic explanation (Ellis, 2019). The challenge lies in linking macro-level ecological interactions to micro-level neurocognitive processes bridging how context shapes neural engagement, plasticity, and memory formation. Without such integration, ecological theories risk remaining descriptive, leaving the neural underpinnings of embodied learning insufficiently theorized.

Emerging neuro-ecological perspectives attempt to address this gap by combining ecological validity with neuroscientific precision. By situating neural activation within authentic digital and social contexts, this approach aligns brain-based evidence with ecological principles of affordances, distributed cognition, and social mediation (Atkinson, 2019). This synthesis

provides a promising direction for understanding how technology-mediated environments co-construct the cognitive and neural systems that underpin second language learning.

4.4 Digital Ecologies and Cognitive Adaptation

Contemporary language learning increasingly unfolds within digital ecologies complex environments in which cognition, technology, and social interaction dynamically intersect. Building on Clark and Chalmers's (1998) notion of the extended mind, digital technologies can be understood as cognitive extensions that externalize and amplify mental processes. When learners engage with digital tools, memory, attention, and linguistic reasoning are not confined to the brain but distributed across interfaces, algorithms, and multimodal inputs. This reconceptualization challenges traditional boundaries of cognition, positioning technological environments as integral components of the learner's neurocognitive system.

Recent advances in virtual reality (VR), artificial intelligence (AI), and multimodal learning platforms have deepened this extension, reshaping how attention, motivation, and linguistic processing operate in technology-mediated contexts. Immersive VR environments elicit heightened sensory engagement and embodied interaction, which have been linked to improved retention and contextualized comprehension (Parmaxi, 2020). AI-driven tutoring systems personalize feedback and adapt to learner performance, activating reward-related neural networks associated with intrinsic motivation (Li, 2022). These technologies do not merely transmit information; they restructure the attentional landscape, shaping how learners allocate cognitive resources and regulate engagement over time.

The affordances of digital tools notably immediacy, interactivity, and multimodality—serve as powerful mediators of cognitive and neural activity. Immediate feedback supports dopaminergic reward responses that enhance memory consolidation, while multimodal stimuli engage distributed sensory and motor networks that facilitate semantic integration (Mayer et al., 2015). Interactive platforms that blend textual, auditory, and visual input mirror the neural integration of multiple modalities in natural communication, fostering deeper encoding and retrieval processes (Kukulska-Hulme & Shields, 2008). Through these affordances, digital systems may scaffold neurocognitive functions much as social environments scaffold learning in ecological models.

At the same time, the adaptivity of digital environments raises important questions about cognitive load and attentional regulation. While AI-based feedback and immersive simulation can enhance focus, excessive interactivity or multimedia saturation may fragment attention, impeding sustained cognitive engagement (Sweller, 2011). Understanding the neural correlates of these dynamics such as oscillatory patterns linked to attentional switching remains an emerging but critical frontier in digital SLA research.

From a neuro-ecological standpoint, technology thus functions as both an environmental affordance and a cognitive prosthesis, influencing how neural systems reorganize in response to learning demands. Studies in neuroeducation suggest that regular engagement with multimodal and interactive media promotes changes in prefrontal and parietal connectivity, indicative of adaptive neuroplasticity (Mårtensson et al., 2012). Yet, this adaptation is not uniformly beneficial; the cognitive and emotional outcomes of digital immersion depend heavily on design, context, and pedagogical alignment.

A recurring critique within the literature is the limited integration of cognitive neuroscience in studies of digital language learning. While digital pedagogy research often highlights sociocultural and ecological dimensions, it rarely examines the underlying neural mechanisms through which technology shapes cognition and language processing (Reinhardt & Thorne, 2020). The absence of neuroscientific data constrains theoretical precision and hampers

understanding of how digital affordances translate into measurable neural engagement or long-term learning outcomes.

Bridging this gap requires a neuro-ecological synthesis that combines the contextual sensitivity of ecological theory with the mechanistic rigor of cognitive neuroscience. Such integration would enable researchers to trace how environmental affordances embodied in digital tools interact with neural systems responsible for attention, motivation, and memory. By conceptualizing digital technologies as extensions of the learner's cognitive architecture, SLA research can more accurately capture the reciprocal adaptation between brain, behavior, and environment in the digital age.

4.5 Emerging Neuro-ecological Perspectives

The field of second language acquisition (SLA) is increasingly turning toward neuro-ecological perspectives that integrate brain-based evidence with ecological and socio-cognitive models. This emerging synthesis conceptualizes language learning as a process of dynamic adaptation within interconnected neural, cognitive, and environmental systems. Rather than treating neural activity and environmental context as separate domains, neuro-ecological approaches emphasize their reciprocal causality the ways in which environmental affordances shape neural organization, and how neural plasticity enables learners to adapt to complex linguistic ecologies (Sporns, 2010; Ellis, 2019).

At its core, the neuro-ecological paradigm builds on insights from complex dynamic systems theory (CDST), which conceives of learners as self-organizing agents situated within adaptive ecosystems (de Bot, Lowie, & Verspoor, 2007). Neural systems, under this view, do not function as static processors but as dynamically responsive networks that reorganize in response to multimodal and social input. This aligns with evidence from neuroimaging research showing that neural connectivity patterns evolve as learners engage in sustained L2 exposure, particularly within immersive or technologically enriched contexts (Li, 2022; Mårtensson et al., 2012). The adaptive reconfiguration of neural pathways thus parallels ecological adaptation both represent processes of systemic alignment between organism and environment.

The integration of brain-based and ecological models marks a conceptual turning point in SLA theory. Traditional neurocognitive research has elucidated the localized mechanisms of language processing such as the roles of Broca's and Wernicke's areas, or prefrontal circuits in attention and working memory but often at the expense of contextual realism (Abutalebi & Green, 2007). Conversely, ecological and sociocultural approaches have richly described the contextual embeddedness of learning but have lacked mechanistic accounts of neural embodiment (van Lier, 2004). Neuro-ecology attempts to bridge these paradigms by treating the brain as an open, environmentally coupled system whose activity is shaped by and helps shape the learner's social, material, and technological world.

In digital contexts, this coupling becomes particularly salient. The integration of AI-driven interaction, multimodal feedback, and immersive environments provides a fertile ground for observing neuro-ecological adaptation in real time. Studies employing EEG and fMRI methodologies have begun to trace how interaction with adaptive digital systems modulates attentional control and memory networks, suggesting that technological affordances may act as cognitive catalysts for neural reorganization (Mayer et al., 2015; Parmaxi, 2020). These findings underscore the idea that digital tools do not merely support cognition—they participate in it, extending the learner's neural ecology into the technological domain (Clark & Chalmers, 1998).

From a theoretical standpoint, neuro-ecology offers a unifying bridge between micro-level neural mechanisms and macro-level contextual dynamics. It reframes cognition as distributed

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across neural and environmental substrates, thus dissolving dichotomies between brain and context, mind and world. Learners are conceptualized as emergent systems; whose cognitive organization reflects continuous negotiation between biological constraints and ecological affordances. This dynamic reciprocity situates SLA within a broader framework of neural-environmental co-adaptation, where learning is both a neurobiological and ecological process. Despite its integrative promise, the neuro-ecological paradigm remains conceptually underdeveloped. Current research tends to operate within parallel, rather than integrated, frameworks neuroscientific studies focus on neural correlates of language processing, while ecological models emphasize interactional complexity and social mediation (Ellis, 2019). The absence of unified theoretical models connecting all three layers neural, cognitive, and environmental limits explanatory coherence. To advance, SLA research must adopt cross-level methodologies capable of linking brain dynamics with ecological variables such as affordances, feedback loops, and technological mediation (Sporns, 2010).

Ultimately, the neuro-ecological perspective invites a systemic reconceptualization of language learning: one that views the learner as a dynamically adaptive node in a distributed cognitive ecology. It challenges reductionist dichotomies between the biological and the social, proposing instead a model of co-constitutive learning, in which neural systems and environmental affordances evolve in tandem. By situating technology within this neuro-ecological continuum, future research can elucidate how digital ecologies co-construct the neural architecture of bilingualism, offering a more holistic account of cognition in the digital age.

4.6 Integrative Neuro-Ecological Synthesis and Theoretical Implications for Digital SLA

The preceding sections converge on a central premise: that second language acquisition (SLA) emerges from reciprocal interactions among neural systems, cognitive processes, and environmental affordances. The neuro-ecological framework unites insights from cognitive neuroscience, ecological psychology, and digital learning theory, positioning language learning as a distributed, adaptive, and co-constitutive process. Rather than treating cognition as an isolated mechanism within the brain, this synthesis emphasizes its embeddedness within sociotechnical ecologies that shape and are shaped by neural and behavioral adaptation.

From the neurocognitive perspective, research has established that L2 learning modifies brain organization and connectivity, particularly in regions supporting working memory, attentional control, and semantic integration (Abutalebi & Green, 2007; Li, Legault, & Litcofsky, 2014). These neural adaptations reflect the brain's inherent plasticity, enabling learners to reorganize cognitive resources in response to environmental stimuli. However, when viewed through an ecological lens, these neural dynamics are not self-contained but contextually modulated they occur within a matrix of social interaction, cultural mediation, and technological engagement. Thus, neuroplasticity is both a biological and ecological phenomenon.

Digital technologies expand this ecological matrix by functioning as cognitive extensions that scaffold, externalize, and transform learning processes (Clark & Chalmers, 1998). Immersive and interactive tools ranging from virtual reality environments to AI-driven language tutors generate novel affordances for linguistic action and reflection. These affordances alter attentional patterns, motivational regulation, and even neural activation profiles, thereby intertwining technological mediation with neurocognitive adaptation (Parmaxi, 2020; Mayer et al., 2015). In this view, digital learning environments are not auxiliary supports but constitutive components of the learner's cognitive ecology.

The integration of ecological and neural perspectives also challenges the methodological divide between experimental neuroscience and authentic learning research. Traditional laboratory

paradigms, while illuminating neural mechanisms, often isolate cognition from the environmental and social contingencies that give it meaning (van Lier, 2004). Conversely, ecological studies, though rich in contextual analysis, rarely provide mechanistic insight into how learning shapes or is shaped by neural processes (Ellis, 2019). A neuro-ecological synthesis overcomes this dualism by conceptualizing cognition as both embodied and emplaced, calling for research designs that capture brain–environment coupling in real or simulated communicative settings.

Theoretically, this integration implies that language learning cannot be reduced either to neural computation or to social participation alone. Rather, it is a process of adaptive attunement, where neural systems, perceptual schemas, and environmental affordances continuously recalibrate one another (Atkinson, 2019). For instance, attentional networks adapt to multimodal digital stimuli, which in turn reshape learners' engagement strategies and meaning-making capacities. The learner's brain becomes an active participant in a broader ecological network, dynamically synchronizing with linguistic, technological, and social inputs.

This synthesis carries significant implications for digital pedagogy and instructional design. Understanding technology as part of the learner's extended cognition necessitates designing environments that foster ecological coherence that is, alignment between cognitive load, sensory affordances, and social interactional patterns. Instructional technologies should not merely replicate classroom input but create adaptive feedback loops that mirror the brain's own self-organizing tendencies. Incorporating neuro-ecological principles could guide the development of AI-based systems capable of responding to learners' cognitive states in real time, optimizing attention and retention while maintaining authenticity and engagement.

Finally, the neuro-ecological framework provides a conceptual bridge for future interdisciplinary research. By integrating methods from cognitive neuroscience (e.g., neuroimaging, EEG), ecological psychology (e.g., affordance mapping), and applied linguistics (e.g., discourse analysis, digital ethnography), scholars can examine how neural, cognitive, and environmental systems co-evolve in digital language learning. Such integration advances not only the explanatory scope of SLA theory but also its relevance to contemporary educational practice, where technology-mediated ecologies are the predominant arenas of linguistic and cognitive development.

4.7 Synthesis and Critical Evaluation

Across the diverse theoretical trajectories examined cognitive, neurocognitive, ecological, socio-cognitive, and digital the evolution of second language acquisition (SLA) research reveals a gradual convergence toward a neuro-ecological synthesis. This synthesis recognizes that language learning is neither purely neural nor purely environmental, but a distributed adaptive process arising from the dynamic interplay between brain, body, and context. Each tradition contributes distinct strengths and faces corresponding limitations, yet collectively they offer complementary insights into the multilayered nature of cognition and learning.

Early cognitive and neurocognitive frameworks provided valuable mechanistic explanations for attention, working memory, and processing efficiency (Baddeley, 1992; Li et al., 2014). Their strength lies in empirical precision and the capacity to map neural activation to linguistic function. However, these models often exhibit a reductionist bias, isolating learning processes from the ecological and social conditions in which they occur. Conversely, ecological and socio-cognitive paradigms highlight the situated, interactive, and embodied nature of language use (van Lier, 2004; Lantolf & Thorne, 2006), yet they frequently lack the neural grounding necessary to explain the biological mechanisms of adaptation. The emerging neuro-ecological paradigm aims to bridge these gaps through cross-level integration, combining the explanatory

rigor of neuroscience with the contextual sensitivity of ecological theory (Ellis, 2019; Sporns, 2010).

A comparative synthesis reveals a pattern of conceptual convergence across traditions. The notion of neuroplasticity within brain-based models aligns closely with adaptability in dynamic systems and ecological accounts; both describe the learner as an organism capable of structural reconfiguration in response to experience. Similarly, the environment in ecological theory parallels the concept of affordance, emphasizing the mutual constitution of learner and setting through action possibilities (Gibson, 1979). Finally, the cognitive emphasis on information processing finds its ecological counterpart in interaction and participation, reframing cognition as emergent from communicative engagement rather than internal computation. These conceptual resonances illustrate that the boundaries between traditions are increasingly porous, inviting synthesis rather than opposition.

In digital learning environments, this synthesis becomes particularly salient. Technologies such as AI, VR, and multimodal platforms serve not only as pedagogical tools but as ecological scaffolds that mediate neural activation, cognitive adaptation, and social engagement (Clark & Chalmers, 1998; Parmaxi, 2020). Through affordances like interactivity and feedback immediacy, digital systems extend the learner's cognitive ecology, providing real-time contexts for neuroplastic adaptation. This demonstrates how environmental design directly interacts with neural dynamics, creating a reciprocal feedback system that underlies effective technology-mediated learning.

Critically, while these insights mark significant theoretical progress, challenges remain in achieving methodological and epistemological integration. Empirical studies often remain confined to either the neural or the sociocultural level, lacking instruments capable of tracing the full neural–cognitive–environmental continuum. To advance, future research must develop multi-level analytical frameworks that can simultaneously capture neural patterns, behavioral adaptation, and ecological engagement in authentic digital settings.

In sum, the synthesis of these traditions supports the emergence of a neuro-ecological model of SLA, wherein language learning is conceptualized as a self-organizing, adaptive system embedded within digital ecologies. This framework unites brain-based mechanisms with environmental scaffolds, offering a holistic explanation of how learners co-adapt across neural, cognitive, and contextual domains. The neuro-ecological paradigm thus represents not merely an integration of existing theories but a transformative lens for rethinking how technology, environment, and the brain co-construct linguistic development in the 21st century.

5. FINDINGS FROM THE THEORETICAL AND LITERATURE REVIEW

The findings drawn from the theoretical framework and literature reviewed reveal a profound transformation in how second language acquisition (SLA) is conceptualized in the digital age. Traditionally, SLA research has been dominated by cognitive and psycholinguistic models that view learning as an internal, information-processing phenomenon. However, the integration of neuro-ecological perspectives disrupts this reductionist view, proposing that language learning is not only a cognitive event but an embodied, situated, and dynamically adaptive process. This shift compels scholars to consider the interaction between neural mechanisms, environmental affordances, and the learner's socio-emotional context.

A key theoretical insight from the neuro-ecological framework is its recognition of the brain's plasticity as deeply influenced by the ecological conditions of learning. Neuroscience has shown that neural pathways reorganize in response to stimuli, attention, and experience. When applied to SLA, this implies that learners' environments digital or physical play a crucial role

in shaping how language is processed and retained. The literature reviewed supports this by demonstrating how interactive digital tools and multimodal input enhance both attentional focus and memory consolidation. This positions the environment as an active participant in the learning process rather than a passive backdrop.

The neuroecological perspective also aligns with ecological theories of learning that emphasize affordances, or the opportunities for action within an environment. From a digital standpoint, platforms such as virtual reality, gaming, and social media provide rich affordances for language practice. These environments elicit authentic communicative engagement, which activates both cognitive and emotional pathways. The literature highlights how this ecological richness facilitates embodied cognition where gestures, perception, and emotion intertwine with linguistic processing. Thus, neuro-ecology bridges the gap between brain-based and context-based explanations of language learning.

Critical examination of the findings reveals that neuro-ecological approaches challenge the dominance of static cognitive models. Whereas traditional SLA frameworks often treat language competence as a stable mental representation, neuro-ecology views it as fluid and contextually emergent. Learners adapt to varying communicative environments by constantly reorganizing neural and behavioral patterns. This view resonates with dynamic systems theory, which conceptualizes language learning as a nonlinear, adaptive process influenced by multiple interacting variables. The literature reviewed supports this dynamic orientation through studies on variability in learner performance and context-sensitive outcomes.

Another crucial implication of the theoretical framework is its insistence on embodiment as central to learning. Neuro-ecological theories argue that cognition is not detached from the body but grounded in sensorimotor experiences. The reviewed literature on digital learning environments demonstrates how gesture-based and immersive technologies activate sensorimotor circuits that enhance comprehension and recall. For instance, learners who physically manipulate digital objects or engage in virtual role-play exhibit stronger neural activation and retention. This underscores the need to view digital SLA not merely as screen-based learning but as a deeply embodied cognitive process.

Emotion and motivation emerge as critical mediators in this framework. Neuro-ecological models acknowledge that affective states regulate attention and neural activation, shaping how effectively learners engage with language input. The literature provides ample evidence that positive emotional engagement—through gamified learning, social collaboration, or creative expression—leads to more robust learning outcomes. Conversely, anxiety and cognitive overload dampen neural efficiency. Therefore, emotional regulation becomes an integral component of neuroecological SLA, linking neural processes with social and psychological dimensions.

In examining the intersection of the theoretical and empirical findings, it becomes clear that the neuroecological approach redefines what constitutes effective learning environments. It suggests that optimal SLA occurs when the digital ecology supports multisensory engagement, social interaction, and emotional resonance. The reviewed studies on virtual exchange, immersive simulations, and AI-driven tutoring reveal that such environments enhance learners' attention, memory, and motivation. These findings challenge pedagogical models that rely on decontextualized drills, advocating instead for experience-rich and ecologically balanced designs.

A recurring theme in both theory and literature is the dynamic interplay between attention and environment. Neuroscientific studies show that attention is not merely an internal process but dynamically guided by environmental affordances. In digital SLA, interactive and adaptive

systems can scaffold attention through multimodal feedback, prompting learners to focus on relevant linguistic cues. The literature confirms that such adaptive feedback mechanisms enhance neural connectivity and reinforce learning. Thus, attention becomes an emergent property of learner-environment coupling rather than a fixed cognitive resource.

The methodological implications arising from these findings are significant. Neuro-ecological research necessitates hybrid methodologies that combine neurocognitive data with ecological observation. This means that brain-imaging techniques such as EEG or fMRI must be complemented with discourse analysis, ethnographic methods, and digital interaction tracking. The literature reveals a growing trend toward such multimodal methodologies, allowing researchers to correlate neural signals with communicative behaviors and environmental variables. This approach captures the complexity of language learning as a living, adaptive system.

However, a critical limitation identified in the reviewed studies is the difficulty of integrating these data streams. Neuroimaging provides precise but contextually limited insights, whereas ecological observation captures real-world dynamics but lacks neural specificity. Theoretical work within the neuro-ecological framework advocates for technological and analytical innovations that bridge this gap, such as portable neuroimaging and AI-driven analytics. These tools would enable researchers to study language learning in authentic digital contexts without sacrificing neurobiological accuracy.

The neuro-ecological interpretation also has profound implications for pedagogy. The literature reviewed suggests that teaching strategies grounded in this framework should emphasize experiential, interactive, and context-sensitive learning. Teachers become designers of learning ecologies that engage the whole learner neurologically, emotionally, and socially. This represents a paradigm shift from transmission-based instruction toward facilitation of embodied engagement. It also demands that digital tools be integrated thoughtfully, ensuring alignment with learners' cognitive rhythms and ecological needs.

From a theoretical standpoint, the neuro-ecological model invites a redefinition of language competence itself. Rather than viewing competence as an abstract repository of linguistic knowledge, it can be seen as a distributed phenomenon emerging from continuous brain-body-environment coordination. This interpretation resonates with ecological linguistics and enactivism, both of which argue that meaning arises through action and perception. The literature supports this claim through studies showing that context-rich and action-oriented learning leads to deeper, more flexible language use.

Critically, this shift challenges long-standing assumptions about individual cognition in SLA. Neuro-ecology contends that cognition is not localized solely within the individual but extends across networks of interaction, tools, and artifacts. This distributed cognition model aligns with findings from digital learning environments, where learners co-construct meaning through social media, collaborative platforms, and virtual communities. The reviewed literature highlights how such distributed processes foster collective intelligence and enhance individual linguistic performance.

The neuro-ecological lens also offers a powerful critique of the notion of input as a static concept. While traditional SLA models emphasize comprehensible input, neuro-ecological approaches view input as dynamically mediated through perception, attention, and context. The quality of input depends not only on linguistic features but also on its ecological resonance its capacity to engage the learner's sensory and emotional systems. The literature reviewed supports this reconceptualization, showing that multimodal, interactive input yields more durable neural activation than text-based exposure.

A particularly illuminating aspect of the literature is its treatment of digital embodiment. Virtual and augmented reality environments enable learners to inhabit linguistic worlds, experiencing language as lived action. Neuro-ecological theory explains the effectiveness of such experiences through embodied simulation, wherein neural circuits for perception and action overlap with those for language processing. Studies confirm that immersive digital learning enhances not only linguistic proficiency but also empathy and intercultural awareness, reinforcing the integrative potential of neuro-ecology.

The theoretical framework also draws attention to the temporal dimension of learning. Neuro-ecological models emphasize that language development unfolds across multiple timescales—moment-to-moment neural activity, session-level engagement, and long-term adaptation. The literature reviewed provides empirical support for this through longitudinal studies demonstrating that consistent engagement with rich digital ecologies leads to cumulative neural and behavioral change. This underscores the need for research designs that capture both micro and macro temporal dynamics.

Critically, the neuro-ecological paradigm calls for a reconceptualization of research ethics and learner agency. As learners become active participants within complex digital ecologies, issues of data privacy, autonomy, and cognitive load must be carefully managed. The literature warns against over-automation and the reduction of learners to data points, advocating instead for designs that prioritize human-centered and embodied interaction. Ethical neuro-ecology thus insists on maintaining balance between technological affordances and the learner's well-being. The convergence of neuroscience and ecology in SLA theory also stimulates dialogue about interdisciplinarity. The literature reviewed reveals that fruitful advances emerge when linguists, neuroscientists, educators, and technologists collaborate. Such partnerships enable the development of integrative models that link neural patterns to communicative practices. Theoretical innovation thus depends on methodological pluralism and epistemic humility, acknowledging the partial insights each discipline contributes.

Another critical discussion centers on the scalability of neuro-ecological principles. While many studies focus on controlled or small-scale environments, broader application requires pedagogical frameworks that translate these insights into curriculum design and teacher training. The reviewed literature suggests that scalable neuro-ecological pedagogy should emphasize flexibility, personalization, and multisensory engagement. This ensures that learners across diverse contexts can benefit from the adaptive power of neuro-ecological learning.

The synthesis of the theoretical framework and literature reviewed highlights a transformative vision for SLA one that situates language learning at the intersection of brain, body, and environment. The neuro-ecological lens not only deepens our understanding of the neural and contextual dynamics of learning but also redefines what it means to acquire and use a language in the digital era. Its critical implications extend beyond theory, demanding new methodologies, ethical considerations, and pedagogical practices that honor the full complexity of human cognition as it evolves within a technologically mediated world.

6. DISCUSSIONS

The neuro-ecological lens provides a holistic framework for interpreting second language acquisition (SLA) by bridging the gap between the cognitive processes of the brain and the ecological contexts in which learning unfolds. It emphasizes that language learning is not confined to neural mechanisms alone but emerges from the continuous interaction between mind, body, and environment. This view challenges traditional dichotomies between internal

cognition and external context, suggesting that language development is an adaptive process shaped by both neurobiological systems and social affordances.

Through this perspective, the digital environment becomes a crucial component of the learner's ecology. Digital tools, platforms, and media reshape sensory engagement and cognitive processing, creating new conditions for language exposure, feedback, and interaction. The neuro- necological approach thus highlights how digital immersion can stimulate neural plasticity, reinforcing the brain's capacity to form and reorganize language networks. This intertwining of digital affordances with neurocognitive processes marks a significant shift in understanding SLA in the 21st century.

A synthesized framework emerging from this perspective integrates findings from neuroscience, cognitive psychology, and ecological linguistics. Such a framework situates language learning as a dynamic system where neural adaptations, embodied interactions, and environmental structures co-evolve. Rather than isolating variables, this integrative model recognizes the feedback loops between digital engagement, attention, and affective regulation. The learner becomes both a biological and ecological agent, whose linguistic growth reflects multi-level coordination across systems.

Central to this synthesis is the idea that embodiment plays a vital role in language learning. Neuro-ecological theory posits that cognition is grounded in sensory and motor experiences, meaning that digital learning environments must engage learners bodily as well as mentally. Gesture-based interfaces, immersive simulations, and multimodal feedback mechanisms all exemplify how digital technologies can activate embodied cognition, enhancing linguistic comprehension and production.

The theoretical implications of this approach point toward a dynamic, embodied model of digital SLA. Such a model conceptualizes learning as an emergent property of real-time interactions between the brain, body, and technological context. It rejects static representations of language knowledge in favor of fluid, adaptive systems that reorganize through continuous practice and feedback. This reframing aligns SLA theory with contemporary understandings of dynamic systems in cognitive science.

Additionally, this embodied model underscores the significance of affect and motivation in digital learning contexts. Neuro-ecological perspectives recognize that emotional engagement modulates neural activity and learning outcomes. Positive affective states such as curiosity or enjoyment in gamified environments can enhance memory consolidation and neural connectivity. Thus, digital SLA is not only a cognitive process but also an affective and experiential phenomenon.

Methodologically, the neuro-ecological approach calls for hybrid neurocognitive–ecological research designs. This means combining neuroimaging or electrophysiological data with qualitative observations of interactional and environmental patterns. For instance, eye-tracking and EEG studies can be integrated with discourse analysis or ethnographic observation to capture both neural and situational dynamics of language learning. Such mixed methods promise a richer, more comprehensive understanding of how learning unfolds in real and virtual ecologies.

This methodological shift also challenges researchers to move beyond laboratory settings. Since neuro-ecological learning is context-sensitive, data should be collected in authentic or semi-authentic digital learning environments. Virtual reality, social media, and online classrooms serve as ecologically valid contexts for examining how brain–environment couplings shape linguistic behavior. This orientation bridges experimental control with ecological validity.

Moreover, the framework encourages interdisciplinary collaboration. Neuroscientists, applied linguists, and digital learning designers must work together to map how cognitive mechanisms translate into educational affordances. By merging insights from multiple fields, researchers can design interventions that optimize both neural efficiency and ecological engagement. This transdisciplinary ethos reflects the integrative spirit of the neuro-ecological paradigm.

In sum, interpreting SLA through the neuro-ecological lens redefines language learning as an embodied, contextually situated, and dynamically evolving phenomenon. The proposed synthesized framework not only unites cognitive and ecological dimensions but also invites methodological innovation and theoretical renewal. As digital technologies continue to mediate how learners interact with languages and environments, a neuro-ecological understanding ensures that SLA research remains responsive to the complexity of human learning in a digitally interconnected world.

7. CONCLUSION AND RECOMMENDATIONS

The emergence of the neuro-ecological perspective marks a pivotal moment in the evolution of second language acquisition (SLA) research, offering a unifying paradigm that bridges the cognitive, affective, and environmental dimensions of learning in the digital era. By viewing language acquisition as an embodied, contextually situated, and dynamically adaptive process, this framework transcends the limitations of traditional cognitive or sociocultural models. It positions the learner not merely as a processor of linguistic input but as an active participant in a living, interconnected ecosystem—where brain activity, bodily engagement, emotional resonance, and digital affordances continuously interact to shape learning outcomes. This integrative understanding of digital SLA underscores the inseparability of neural processes and environmental contexts, affirming that effective language learning emerges from the reciprocal interplay between the mind, the body, and the technological world.

In reflecting upon the findings and theoretical discussions presented in the preceding chapters, it becomes clear that the neuro ecological paradigm does more than reinterpret existing knowledge it reframes the research agenda for digital language learning. Despite its transformative potential, several critical gaps remain. Empirical evidence linking neural mechanisms to ecological variables in authentic digital environments is still limited, and methodological approaches capable of capturing these dynamic interactions are underdeveloped. The need for interdisciplinary collaboration, longitudinal designs, and ethically grounded technological integration remains urgent. Consequently, the following sections synthesize the key insights derived from this study and propose forward-looking recommendations for advancing both theory and practice. Together, these insights reaffirm the neuro-ecological perspective as a foundational and unifying framework capable of guiding the next generation of SLA research in a rapidly evolving digital landscape.

7.1 Summary of Key Insights

The neuro-ecological perspective offers a transformative and unifying paradigm for understanding digital second language acquisition (SLA), one that integrates insights from neuroscience, cognitive science, ecology, and applied linguistics. This framework emphasizes that language learning is not merely a mental process housed within the brain but an embodied and contextually situated phenomenon shaped by the dynamic interplay between neural systems, environmental affordances, and social interaction. Within digital environments, this approach recognizes that cognition, perception, and emotion are continuously modulated by technological interfaces and virtual contexts. Thus, the neuro-ecological model positions the

learner as both a biological and ecological agent adapting, interacting, and co-constructing meaning through complex neural-environmental feedback loops.

One of the key insights emerging from this perspective is its ability to bridge the traditional divide between cognitive and sociocultural theories of SLA. Whereas cognitive models focus on information processing and neural mechanisms, and sociocultural theories emphasize interaction and context, the neuro-ecological paradigm synthesizes both, proposing that language learning emerges from the ongoing coordination of brain, body, and environment. Digital learning settings such as immersive simulations, online collaboration, and multimodal communication—serve as rich testing grounds for this synthesis, allowing researchers to observe how neural plasticity and environmental engagement mutually reinforce each other. This integrative view highlights the need to study language acquisition not as an isolated cognitive function but as a dynamic, adaptive, and context-sensitive process.

The neuro-ecological framework also underscores the significance of embodiment and affect in digital language learning. Learners' physical actions, gestures, and emotional states directly influence neural activation and cognitive performance. Digital tools that enable sensory and motor engagement such as virtual reality, augmented reality, and gamified platforms enhance language acquisition by activating embodied cognition. Moreover, the affective dimension, including motivation, curiosity, and emotional resonance, plays a vital role in shaping neural pathways and memory consolidation. By acknowledging these factors, the neuro-ecological approach provides a more holistic account of how learning unfolds in technologically mediated environments, emphasizing that emotion and embodiment are not peripheral but central to cognitive development.

Despite its promise, the literature reveals several critical research and theoretical gaps that must be addressed. Empirical studies directly linking neural data with ecological variables in authentic digital settings remain scarce, limiting the robustness of the framework. Methodologically, there is a pressing need for hybrid neurocognitive–ecological research designs that integrate neuroimaging, behavioral observation, and digital interaction analysis.

Furthermore, longitudinal studies are needed to capture the temporal dynamics of how neural and ecological systems co-evolve during the language learning process. Theoretical gaps also persist in operationalizing core concepts such as affordances, embodiment, and neuroplasticity within digital contexts, calling for clearer conceptual models and interdisciplinary collaboration.

In summary, the neuro-ecological perspective offers a comprehensive and forward-looking framework for digital SLA, yet it remains in its developmental stage. It provides powerful explanatory tools for understanding how neural, affective, and environmental processes interact, but it also challenges researchers to rethink traditional methodologies and theoretical boundaries. Addressing the identified gaps will require sustained collaboration across neuroscience, linguistics, education, and technology studies. Ultimately, advancing this paradigm promises to produce a more complete understanding of language learning as a dynamic, embodied, and ecologically embedded process one that reflects the realities of human cognition in an increasingly digital and interconnected world.

7.2 Theoretical Implications

Reframing digital learning as a co-adaptive system of brain–environment coupling represents a significant theoretical advancement within the field of second language acquisition (SLA). This perspective challenges the long-standing assumption that language learning occurs primarily within the individual mind, emphasizing instead that cognition emerges through dynamic interactions between neural processes and environmental structures. In digital

contexts, learners continuously adapt to technological affordances, feedback mechanisms, and social dynamics, while these environments, in turn, evolve in response to user engagement. This reciprocal adaptation what neuro-ecology identifies as co-adaptive coupling suggests that learning is not a one-directional process of information intake, but a bidirectional, embodied negotiation between the brain's plastic systems and the digital ecology it inhabits.

The theoretical implications of this view extend beyond a redefinition of the learning process to a reorientation of how we conceptualize cognition itself. Rather than viewing the brain as an isolated information processor, the neuro-ecological framework positions it as part of an extended cognitive system distributed across neural, bodily, and environmental networks. In digital learning, this means that cognition is embedded in interfaces, mediated through technological tools, and shaped by multimodal interactions. The learner's attention, emotion, and sensory engagement are continuously modulated by these digital affordances, forming adaptive feedback loops that restructure both neural connections and behavioral strategies. Consequently, learning becomes a process of systemic synchronization, where the brain and environment co-regulate each other toward greater communicative and cognitive efficiency.

This co-adaptive model also invites a reconceptualization of digital environments as more than instructional platforms they function as cognitive ecosystems that actively participate in meaning-making. Every aspect of the digital ecology visual layout, interactivity, social connectivity, and sensory input acts as a cognitive scaffold that guides perception and thought. When learners interact within such environments, they are not merely consuming information but reshaping their neural and perceptual systems in accordance with the affordances provided. This mutual adaptation suggests that effective digital pedagogy must design environments that foster optimal brain–environment alignment, balancing cognitive challenge with emotional engagement and ecological coherence.

Furthermore, the co-adaptive framework blurs the boundaries between the internal and external dimensions of learning, situating language acquisition within a continuum of neural and environmental change. The brain's plasticity allows it to internalize ecological structures, while the environment adapts through learner-driven customization and feedback. In digital SLA, this manifests in personalized learning systems that evolve in response to users' cognitive patterns, effectively forming an interactive symbiosis between technology and mind. This dynamic reciprocity has profound implications for understanding individual differences in learning, as it highlights that success in language acquisition depends not only on neural capacities but also on the adaptability of the learning ecology itself.

Ultimately, framing digital learning as a co-adaptive system of brain–environment coupling transforms the theoretical foundations of SLA. It shifts the field from a static, internalist conception of learning toward a dynamic, relational, and embodied paradigm. This perspective underscores that cognition is inherently ecological shaped by sensory experience, emotional resonance, and technological mediation. By embracing this holistic understanding, researchers and educators can better design learning systems that cultivate synergy between the neural, emotional, and ecological dimensions of human learning. In doing so, the neuro-ecological framework provides not only a more accurate model of digital SLA but also a compelling vision for the future of education in an increasingly interconnected and adaptive world.

7.3 Practical Implications

The neuro-ecological perspective provides a robust foundation for developing design principles that inform the creation of digital learning tools aligned with how the brain, body, and environment interact during the language acquisition process. By viewing digital SLA as a co-adaptive system, designers and educators are encouraged to move beyond traditional

instructional paradigms toward environments that support embodied, affective, and contextually grounded learning. Neuro-ecologically informed tools must therefore be designed to stimulate neural plasticity, engage sensorimotor systems, and foster meaningful interaction within authentic digital ecologies. Such tools should not only deliver information but also cultivate adaptive engagement between learners and their environments, promoting deep cognitive and emotional resonance.

A primary design principle emerging from this framework is embodied interaction. Learning interfaces should encourage physical engagement through gesture recognition, movement-based input, and multimodal feedback to activate the sensorimotor circuits associated with linguistic comprehension and production. Virtual and augmented reality platforms, for example, can immerse learners in rich communicative contexts where language is experienced through action and perception rather than passive observation. This kind of embodied design not only enhances retention but also aligns with the brain's natural way of integrating sensory and linguistic information, making learning more intuitive and neurologically grounded.

A second essential principle involves affective engagement and motivation. Neuroscientific evidence highlights that emotional states modulate attention, memory, and neural efficiency. Consequently, digital learning tools should incorporate elements that evoke positive affective responses such as narrative immersion, gamification, personalization, and creative expression. These emotionally resonant features help sustain motivation and foster a sense of agency, which in turn supports the co-adaptive process between learner and environment. Designing for emotional engagement ensures that digital SLA environments not only stimulate cognitive effort but also maintain learners' psychological and motivational well-being.

Another critical design consideration is ecological authenticity, which entails situating learning within contexts that mirror real-world communication and interaction. Neuro-ecologically informed digital tools should provide environments where learners can engage in purposeful, socially meaningful language use. This could include virtual exchanges with native speakers, collaborative problem-solving tasks, or AI-driven simulations of authentic communicative scenarios. Such ecologically rich contexts promote the integration of cognitive, social, and affective systems, allowing learners to internalize language as a lived, adaptive process rather than a set of abstract rules.

Finally, the neuro-ecological approach advocates for adaptive feedback and personalization as central features of digital learning design. Since the brain–environment relationship is dynamic and individualized, tools should be capable of responding to learners' changing cognitive and emotional states. Through real-time analytics, biometric input, or adaptive AI algorithms, learning environments can adjust the complexity, pacing, and modality of instruction to maintain optimal engagement and cognitive challenge. This continuous calibration supports neural efficiency and prevents both cognitive overload and disengagement.

In summary, neuro-ecologically informed design principles emphasize embodied interaction, affective engagement, ecological authenticity, and adaptive personalization as key components of effective digital SLA tools. When implemented coherently, these principles transform digital learning environments into living, interactive ecosystems that resonate with the learner's neural, emotional, and social systems. Such designs not only enhance language acquisition but also model the broader co-adaptive relationship between humans and technology—an essential paradigm for the future of education in an increasingly interconnected and neurocognitively informed world.

7.4 Recommendations

Future research on digital second language acquisition (SLA) within the neuro-ecological framework should prioritize the integration of neuroimaging, ecological data, and learning analytics to capture the full complexity of brain–environment interactions. This integrated approach would enable researchers to observe how neural mechanisms, embodied experiences, and environmental affordances co-evolve during language learning. Traditional SLA research methods have often isolated cognitive or contextual variables, but neuro-ecological inquiry demands a multi-layered perspective that connects neural activity to authentic learning behaviors in real or simulated environments. Such integration would not only strengthen theoretical coherence but also generate actionable insights for designing adaptive digital learning systems that align with the brain's dynamic functioning.

To begin with, neuroimaging technologies such as functional near-infrared spectroscopy (fNIRS), electroencephalography (EEG), and functional magnetic resonance imaging (fMRI) should be leveraged to explore the neural correlates of digital language learning in ecologically valid settings. Unlike static laboratory experiments, future research should employ portable and less intrusive neuroimaging tools, allowing learners to engage naturally with digital platforms while their neural responses are recorded in real time. For example, fNIRS and EEG headsets can track neural activation patterns associated with attention, emotion, and language processing as learners interact with multimodal digital tasks. These data can provide direct evidence of how specific design elements such as feedback timing, interactivity, or sensory input affect neural plasticity and learning efficiency.

In parallel, researchers should collect ecological and behavioral data that reflect the learner's interaction with the digital environment. This includes eye-tracking data, movement patterns, communication logs, and even physiological signals like heart rate variability or galvanic skin response. When analyzed alongside neural data, these ecological indicators can illuminate how learners' sensory engagement and emotional states shape their learning trajectories. For instance, combining EEG measures of cognitive load with eye-tracking data could reveal how attention shifts during complex multimodal input, providing insight into how learners manage sensory and linguistic information in digital spaces. The integration of such ecological data ensures that neural findings are interpreted within the context of authentic human–environment interaction rather than abstracted cognitive functions.

The incorporation of learning analytics further enhances this integrative model by enabling large-scale, continuous monitoring of learner behavior within digital systems. Learning management systems, intelligent tutoring platforms, and educational games generate rich streams of data that can reveal patterns of engagement, persistence, and adaptation over time. By combining these analytics with neuroimaging and ecological data, researchers can develop predictive models of learning that identify when and how neural and behavioral adaptation occur. Machine learning algorithms could detect signatures of effective learning states or cognitive overload, providing real-time insights that guide instructional design and personalized feedback. This fusion of data types supports a truly data-ecological neuroscience of language learning one that captures both micro-level neural processes and macro-level behavioral patterns.

Furthermore, future research should focus on developing hybrid methodological frameworks that integrate these data sources through advanced statistical modeling and artificial intelligence. Multimodal data fusion techniques, such as dynamic systems modeling, graph theory, and neural network analysis, can help researchers visualize and interpret the complex coupling between the brain and its digital environment. Collaborative, interdisciplinary research teams comprising neuroscientists, linguists, data scientists, and educational

technologists will be essential for this endeavor. Such collaborations can also promote ethical best practices, ensuring that neurodata and learning analytics are collected, stored, and analyzed responsibly, with full transparency and learner consent.

Finally, future studies must address longitudinal and cross-contextual dimensions of digital SLA. Language learning is not a momentary neural event but a gradual adaptive process unfolding over time and across varied ecological conditions. Long-term research integrating neuroimaging, ecological, and analytics data could reveal how neural adaptations stabilize, how emotional engagement evolves, and how learners transfer skills across digital and real-world contexts. Additionally, cross-cultural studies could explore how different digital ecologies influence the brain–environment relationship in multilingual settings, enriching the global applicability of neuro-ecological principles.

In conclusion, the integration of neuroimaging, ecological data, and learning analytics represents the next frontier in digital SLA research. This holistic approach will enable a more nuanced understanding of how neural, affective, and environmental systems co-adapt during language learning. By embracing such interdisciplinary and technologically advanced methodologies, researchers can move beyond theoretical abstraction toward evidence-based, neuro-ecologically grounded practices that redefine how we design, implement, and assess digital language learning in the 21st century.

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