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EEG Correlates of Language Proficiency: A Systematic Review with Theoretical Analysis

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Abstract: The assessment of language proficiency through traditional testing methods imposes a significant resource burden in educational settings. Electroencephalography (EEG) provides neurophysiological evidence of language proficiency by assessing neural oscillations that reflect the brain's underlying learning mechanisms and cognitive readiness. This systematic review synthesizes findings from 19 studies to see whether brainwave measures can serve as dependable proxies for proficiency and to identify which view of proficiency, including linguistic, functional/communicative, cognitive/academic, and socio-cultural, has received the most attention in the oscillation literature. To that end, we searched several major databases for peer-reviewed international studies published over the past decade, from 2015 through 2025. The reviewed literature reveals robust correlations between neural oscillatory activity and language proficiency, with findings that differ across frequency bands, age groups, and populations. The results also indicate a dominance of cognitive and linguistic perspectives on language proficiency. Brainwave markers show promise as a complementary tool for supporting, rather than replacing, standard assessments, though further validation is still required. Their value lies in opening up new avenues for studying the brain's role in language learning.

Keywords: EEG, Functional Connectivity, Language Proficiency, Neural Oscillations, Resting-State, Second Language Acquisition, Spectral Power, Systematic Review.

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Introduction

A significant challenge in English language instruction is the frequent assessment of students' language proficiency (AlShraah et al., 2024; Emsawas et al., 2025; Ihara et al., 2021; Mariani et al., 2024), a difficulty that may stem in part from the complex definition and multidimensional construct of proficiency itself (Ashofteh et al., 2023). Language proficiency is conceptualized as the interaction between four core linguistic elements (pronunciation, grammar, lexicon, and cultural meaning) and four key language skills (speaking, listening, writing, and reading) (Hulstijn, 2011; Leclercq et al., 2014). Learners may develop disparately across individual skills, with each competency functioning as a distinct, measurable variable rather than as part of a unified progression. In addition to this definition, two complementary forms of language proficiency were formally defined as Basic Language Cognition (BLC) and Higher Language Cognition (HLC). BLC comprises the core, largely implicit knowledge of phonology, morphology, and syntax, alongside explicit lexical knowledge, processed with automaticity and restricted to high-frequency structures common to all adult native speakers. HLC extends beyond this, involving comprehension and production of low-frequency lexicon and complex morphosyntactic structures across written and spoken modalities, typically required for specialized academic, professional, or technical discourse (Hulstijn, 2015). Given this fragmented and multi-layered view of proficiency, it is unsurprising that both scholars and practitioners continue to struggle with how best to capture it in practice.

The ongoing disagreement over what constitutes language ability, along with proficiency's inherently multidimensional character, undermines efforts to create uniform evaluation methods and prevents meaningful cross-study comparisons. Compounding this issue, the significant time and expense required for repeated testing of such a complex trait have increased interest in more objective, less invasive approaches. EEG has risen to prominence as a promising alternative, offering a way to assess language proficiency by capturing brainwave fluctuations that reflect cognitive processing during learning. These neural rhythms constitute a measurable electrophysiological index of skill level, showing promise as a supportive tool that corroborates traditional assessments through neural-behavioral alignment. Given these developments, synthesizing findings from existing EEG studies becomes essential to determine to what extent neural measures consistently reflect the multifaceted nature of proficiency.

Analyzing 19 peer-reviewed studies from the last decade (2015–2025), this systematic review examines how reliably brainwave measurements reflect language ability. It seeks to

determine if neural responses to proficiency are marked by consistent trends or significant contradictions. The study goes beyond a mere synthesis of findings by applying a four-perspective framework (i.e., linguistic, functional/communicative, cognitive/academic, and socio-cultural). These four perspectives directly reflect the four major theoretical traditions that have defined language proficiency over the past decades and remain foundational in applied linguistics and language testing (Gold, 2021; Leclercq et al., 2014). Alternative models map onto these axes rather than replacing them. Beyond classification, this approach brings to light a theoretical imbalance: it remains unclear which of these perspectives has been more extensively examined in relation to brain oscillations, and which ones warrant further empirical attention. Therefore, in this systematic review, there are two main research questions, as follows:

RQ1: What specific neural markers, including spectral power, connectivity, and lateralization, consistently correlate with language proficiency, and where do findings diverge based on age and linguistic background?

RQ2: Among the four perspectives (i.e., linguistic, functional/communicative, cognitive/academic, and socio-cultural), which has received the greatest scholarly attention in EEG-based research on language proficiency?

Literature Review

Theoretical Framework

Key scholars have defined language proficiency along different dimensions. Chomsky (1965) framed it linguistically as mastery of syntactic, morphological, and phonological rules for producing grammatically correct sentences. Expanding on this, Hymes (1972) introduced communicative competence, emphasizing socially appropriate and effective language use. Halliday (1972) rejected previous emphasis, defining language instead as "meaning potential", the meaning choices available to speakers in social settings. He framed meaning potential not in terms of the mind but in terms of the culture. Cummins (1979) distinguished between basic interpersonal communication skills (BICS) and cognitive academic language proficiency (CALP), the latter involving higher-order thinking like analysis and synthesis. Later on, Cummins (2000) found that the BICS/CALP proficiency distinction ultimately created misconceptions about the construct of language proficiency and underscored the dynamic nature of proficiency. Building on these and other definitions in the field, language proficiency can be understood as a multidimensional construct that can be defined from at least four distinct perspectives: Linguistic perspective (Chomsky, 1965), Functional/

Communicative perspective (Hymes, 1972), Socio-Cultural perspective (Halliday, 1972), and Cognitive/Academic perspective (Cummins, 1979). These perspectives represent the foundational theoretical frameworks proposed by key figures in the field to define the multidimensional construct of language proficiency. These perspectives map onto the reviewed EEG literature through distinct operationalizations. The Cognitive perspective links standardized test scores and neurobiological readiness to resting-state brainwaves. The Linguistic perspective is captured through tasks assessing formal structures, syntax, morphology, and orthography. The Functional perspective is reflected in research employing goal-directed scenarios and communicative success measures. Finally, the Socio-Cultural perspective is incorporated via social background questionnaires examining how environmental language use modulates neural connectivity.

This same four-part framework also directly informs the design and interpretation of widely used proficiency assessments. Proficiency is being measured through broadly used tests, each of which addresses one or more of the four perspectives above (Gold, 2021). For example, the TOEFL (Test of English as a Foreign Language) and IELTS (International English Language Testing System) primarily emphasize the linguistic perspective through grammar and vocabulary in context, with the functional/communicative perspective playing a secondary role via speaking and listening tasks that simulate real-world academic and social interactions. In contrast, the TOEIC (Test of English for International Communication) leans heavily on the functional/communicative perspective, measuring the ability to use English in everyday workplace and practical situations. Meanwhile, the Pearson Test of English (PTE) and Duolingo English Test (DET) combine the linguistic and cognitive/academic perspectives with automated scoring of integrated skills. However, the costs associated with the repeated preparation and administration of these tests represent a substantial burden on educational resources (Emsawas et al., 2025).

Empirical Studies

Emsawas et al. (2025) have indicated that neurophysiological measures, specifically electroencephalography (EEG), can serve as viable alternatives for evaluating second language (L2) proficiency. As for the first language (L1), some studies revealed the predictive effect of resting EEG power in L1 literacy (Lui et al., 2021; Zhang et al., 2025), while others investigated only the relationships between EEG measures and language abilities (Alvarez-Alonso et al., 2025; Lum et al., 2022). These measures are grounded in the electrophysiological properties of the brain, which are characterized by rhythmic neural

activity. Neural oscillations are divided into five frequency bands linked to different cognitive states. Delta waves (<4 Hz) occur during deep sleep and aid memory consolidation (Aparnathi & Dwivedi, 2014). Theta waves (4-8 Hz) appear during relaxation, intellectually demanding tasks, and hippocampal memory processes (de Beeck & Nakatani, 2019; Raghavachari et al., 2001). Alpha waves (8-13 Hz) emerge with eyes closed and reduce during active task engagement (de Beeck & Nakatani, 2019). Beta activity (13–30 Hz) indexes focused attention, active cognition, and motor preparation, whereas gamma oscillations (30–100 Hz) underpin memory encoding, attentional control, and higher-order reasoning (de Beeck & Nakatani, 2019).

Extending this framework, Emsawas (2025) measured frontal theta activity via EEG as an online marker of concentration during L2 (English) learning tasks. Analysis of the frontal theta oscillations revealed that advanced students exhibited higher levels of this concentration-related brain activity compared to their beginner-level counterparts. A number of studies (e.g., Prat et. al, 2016, 2019) have investigated the potential of quantitative electroencephalography (qEEG) to anticipate variations in L2 learning speed and the frequency of speech attempts. In terms of the effect of L2 proficiency on the neural representation of phonemes, Di Liberto et al. (2021) developed a methodological framework to enable a more comprehensive investigation of language processing under natural conditions by recording EEG signals from native and non-native English speakers while they listened to English audio. The impact of L2 proficiency was particularly evident in the neural representation of phonemes, with proficient learners demonstrating enhanced encoding of phonemic contrast absent in their native language (Mandarin). Notably, individuals with higher proficiency levels presented linguistic feature representations that were increasingly similar to those of native speakers, facilitating accurate proficiency assessment. These findings contribute to our understanding of cortical language processing in L2 learners and introduce an objective measure of language proficiency, yet they rely on cross-sectional designs and tasks that limit generalization.

Furthermore, Kwok et al. (2019) investigated the relationship between resting-state EEG alpha power and language abilities in a cohort of children aged 4 to 6 years. Assessing grammatical, syntactic, and lexical skills in expressive and receptive domains, they found that alpha oscillation characteristics, specifically their power, frequency flexibility, and temporal correlation, were associated with children's outcomes on a standardized language assessment. These results imply that uncovering the contribution of neural oscillations to cognitive

processes may necessitate a thorough investigation of oscillator properties using diverse analytical approaches.

In addition, Maguire and Schneider (2019) compared resting-state EEG and performance on a battery of language and cognitive assessments in 45 children aged 8–15 years from low-income households and a matched group of 45 same-age and same-sex peers from higher-income households. Children from low-income backgrounds exhibited poorer performance on language tasks and showed distinct resting-state EEG patterns, including higher theta power and lower alpha power. Lower resting theta power predicted better working memory in both groups. By contrast, the relationship between resting alpha power and vocabulary attainment was significant only among low-income children, with greater alpha activity linked to higher scores in that subgroup alone. These findings lend support to the view that the socioeconomic differences seen in resting-state EEG reflect a developmental delay among children from lower-income households, rather than a fundamentally deficient or abnormal trajectory of brain development (Hoff, 2013). This developmental lag is likely attributable to greater exposure to risk factors that are more prevalent in low-income households, including inadequate nutrition during prenatal, infant, and childhood stages, higher environmental and home-related stress, lower levels of parental responsiveness and engagement, and reduced access to high-quality linguistic and cognitive stimulation (Evans & English, 2002; Hoff, 2013).

Current Study and Research Gap

Despite growing research on the neurophysiological basis of language proficiency and its potential for brain-based assessment, a synthesis consolidating existing evidence to reveal the overall pattern is still absent. Moreover, to resolve ongoing definitional debates, the authors interpret the neurological findings through four complementary lenses, including linguistic, communicative, cognitive, and socio-cultural, to ascertain which theoretical paradigms are most prominent in the current academic discourse. Altogether, the remainder of this paper is structured as follows. Section 3 details the PRISMA-guided methodology used to identify and select the 19 core studies for analysis. Section 4 synthesizes the neural correlates of proficiency and evaluates them against the four theoretical perspectives. Finally, Section 5 provides concluding remarks, synthesizing the evidence and outlining future research directions.

Methods

This systematic review followed the updated PRISMA 2020 guidelines to keep things transparent and thorough (Page et al., 2021). To ensure complete compliance, the completed PRISMA 2020 checklist (see Appendix, Table A1) was reviewed and verified by all authors prior to the final analysis, confirming that all essential items were addressed and reported. We put together a targeted search strategy and ran it across several major multidisciplinary databases. For the main search, we used Google Scholar, PubMed, and ScienceDirect because they index a wide range of reputable, peer-reviewed content across the sciences, medicine, technology, and social sciences. Since the field moves fast, we limited the search to work published between January 2015 and August 2025 to make sure we were capturing the most recent developments and findings. The search covered 2015–2025 to capture recent advances in this fast-moving field. This timeframe ensures the review incorporates findings from the latest EEG technologies and analytical approaches, including resting-state connectivity and network modularity, that have emerged over the past decade.

The search strategy combined discipline-specific keywords with controlled vocabulary terms aligned with the core constructs under investigation, namely "EEG resting-state brainwave activity", "foreign/second language proficiency", and the four primary language modalities "reading", "writing", "listening", and "speaking". These terms were iteratively refined and logically combined, thereby optimizing the retrieval of methodologically relevant studies. For each record identified through this process, a standardized data extraction form was employed to capture a consistent set of variables. Extracted information included bibliographic descriptors (authors, publication year, publisher, and country of origin), performance indicators such as citation counts, and persistent identifiers including DOIs, all of which supported subsequent analysis, reference tracking, and source verification.

For the search in databases, we used the following search string.

Google Scholar: ("EEG" OR "resting-state brainwave activity" OR "resting-state EEG") AND ("foreign language proficiency" OR "second language proficiency" OR L2) AND (reading OR writing OR listening OR speaking).

PubMed: ((("Electroencephalography"[tiab]) OR "EEG"[tiab] OR "resting-state brainwave activity"[tiab] OR "resting-state EEG"[tiab]) AND (("Language Proficiency"[tiab]) OR "foreign language proficiency"[tiab] OR "second language proficiency"[tiab]) AND "reading"[tiab] OR "writing"[tiab] OR "listening"[tiab] OR "speaking"[tiab]))

ScienceDirect: (("EEG" OR "resting-state brainwave activity") AND ("foreign language proficiency" OR "second language proficiency") AND ("reading" OR "writing" OR "listening" OR "speaking"))

Following the PRISMA framework, we predefined inclusion and exclusion criteria and applied them across two independent screening stages to minimize bias and improve selection reliability. Independent screening of all studies was performed by two reviewers (Author A and Author B). In cases of disagreement, resolution was achieved through discussion or the involvement of a third reviewer. Inter-rater reliability, measured by Cohen's Kappa, was 0.85, denoting strong agreement. Disagreements were logged and resolved by consensus or third-reviewer adjudication prior to data extraction.

Inclusion Criteria

- **Publication Type:** The review considered peer-reviewed journal publications, including research articles.
- **Language:** Only sources published in the English language were included.
- **Publication Date:** The selected publications were confined to those issued within the timeframe of 2015 to 2025.
- **Methodology:** Studies utilizing resting-state or task-based EEG were investigated.
- **Thematic Focus:** The central focus was on studies investigating the association of neural oscillations and language proficiency.

Exclusion Criteria:

- **Publication Type:** Non-journal literature, including books, book chapters, dissertations, theses, and conference proceedings was excluded.
- **Language:** Any source not published in the English language was omitted from the review.
- **Publication Date:** Publications dated prior to 2015 were deemed outside the scope of this study.
- **Thematic Relevance:** Studies that employed EEG but were not directly pertinent to language acquisition and language proficiency were excluded.

Review Process

As illustrated in Figure 1, the literature selection process was executed in a multi-stage, systematic manner to ensure a rigorous and replicable methodology.

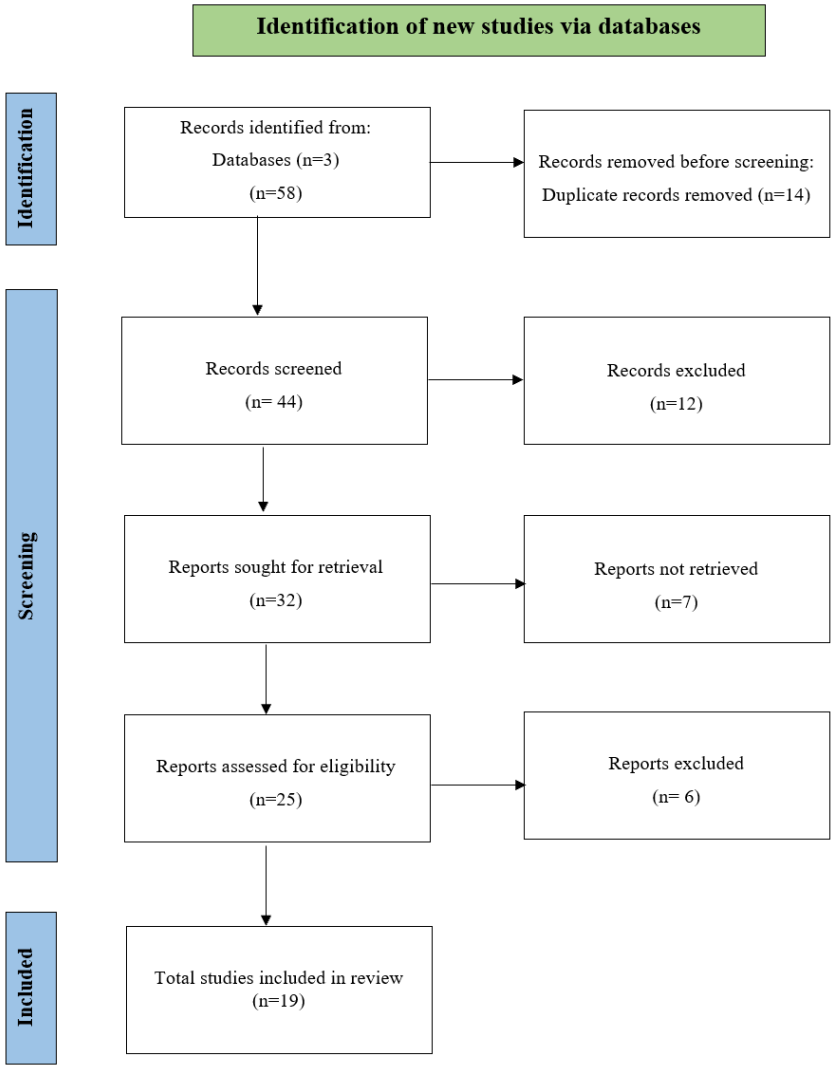


Figure 1. PRISMA Diagram of the Selection Process of Articles

1. Primary Search: The initial phase involved conducting a comprehensive electronic search within Google Scholar, PubMed, and ScienceDirect databases, selected for their robust indexing of high-quality, peer-reviewed literature (n=58). Before the first screening, 14 articles were excluded because they were duplicate records (n=44).

2. First Screening (Title and Abstract): The first screening involved a preliminary evaluation of titles and abstracts. During this stage, the eligibility of each study was assessed based on the predefined inclusion and exclusion criteria, focusing on the relevance of the title and abstract to the PICOS framework. Using the PICOS framework, this review encompassed a broad population (P), including young children (ages 4–15), adults (18–48), and older adults (65–73), including both monolingual and bilingual speakers. The intervention or exposure (I) required eligible studies to employ

resting-state or task-based EEG for measuring dynamic brainwave activity. For the comparison (C), studies primarily adopted cross-sectional group contrasts such as proficient versus struggling readers or bilingual versus monolingual participants, alongside individual-differences designs. The primary outcome (O) was the association between neural oscillations (in terms of spectral power, connectivity, or lateralization) and language proficiency. Regarding study design (S), the included works featured cross-sectional, longitudinal, and experimental approaches; although most were cross-sectional, longitudinal investigations, for instance, tracking children from Grade 2 to 6 or monitoring adults over an 8-week language training period, were also incorporated to capture developmental and learning trajectories over time. Thirty-two articles were retained based on this framework, and twelve articles were removed (n=32).

3. Second Screening (Full-Text Assessment): The second screening entailed a meticulous examination of the full-text articles against the predetermined inclusion and exclusion criteria. Following this stringent evaluation, twenty-five articles were advanced for final analysis, while seven articles were excluded due to content redundancy (n=25).

4. Final Analysis and Data Extraction: A full-text, in-depth review was conducted on the twenty-five qualifying articles. A narrative synthesis was subsequently performed, organizing findings thematically by neural oscillation metrics and language modalities, and structured according to the four-perspective framework (linguistic, functional/communicative, cognitive/academic, and socio-cultural) to examine proficiency operationalizations. Subsequently, data were systematically extracted from nineteen studies that offered unique contributions. The final six articles were excluded due to methodological concerns (n=19).

Quality and Risk of Bias Assessment

The methodological quality and risk of bias of the included studies were assessed using the appropriate Joanna Briggs Institute (JBI) Critical Appraisal Checklist according to the design of each study (Munn et al., 2020). Specifically, the JBI Critical Appraisal Checklist for Cohort Studies, Quasi-Experimental Studies, or Analytical Cross-Sectional Studies was applied as appropriate. Each checklist item was rated as Yes, No, Unclear, or Not Applicable. For descriptive purposes only, Yes responses were assigned a score of 1, whereas No and Unclear responses were assigned a score of 0. Items rated Not Applicable were excluded from the denominator when calculating the overall score. Studies with 7-8 affirmative

responses (≥88%) were classified as high quality (low risk of bias), those with 5-6 affirmative responses (63-75%) as moderate quality (moderate risk of bias), and those with 0-4 affirmative responses (≤50%) as low quality (high risk of bias). These classification thresholds were defined a priori by the authors to facilitate interpretation. Among the 19 included studies, 14 studies (73.7%) were classified as having high methodological quality and 5 studies (26.3%) were classified as having moderate methodological quality (see Appendix, Table A2 for details).

Operationalization of the Four Perspectives

To categorize the reviewed studies, we adopted a systematic framework aligned with each perspective's prevalent operational definition:

Linguistic perspective is defined as studies employing formal structural measures, including but not limited to the Nelson Denny Reading task, word discrimination task, semantic generalization task, recalling sentence subtest, DELE, TOEIC, EIKEN test, listening comprehension, L2 comprehension, PROLEC-SE-R, artificial language learning task, orthographic awareness testing, word list reading, and grammaticality judgments.

Cognitive/academic perspective is defined as research utilizing standardized test scores or neurobiological markers of learning readiness, such as the Simon task, nonverbal reasoning, verbal reasoning, nonverbal IQ test assessed by Raven's Standard Progressive Matrices, RAN, verbal working memory, attention, Wechsler Adult Intelligence, L2 aptitude variable, Llama language aptitude test, executive functioning, RAPM (Raven's Advanced Progressive Matrices), and resting-state EEG.

Functional/communicative perspective is defined as investigations centered on goal-oriented, real-world communication tasks, for instance, virtual reality scenarios and speech attempts.

Socio-cultural perspective is defined as studies emphasizing social context measures, including socioeconomic status (SES), the Language and Social Background Questionnaire (LSBQ), and the Language Experience and Proficiency Questionnaire (LEAP-Q) for assessing language use patterns.

To minimize subjectivity, two independent reviewers initially categorized each study, with disagreements resolved through consensus discussion or third-party adjudication. Two independent coders applied these a priori criteria; inter-rater reliability for the four-perspective categorization was $\kappa = 0.82$ (95% CI [0.68, 0.96]), indicating strong agreement. Disagreements were resolved through consensus discussion or third-party adjudication.

Overlaps were acknowledged and discussed rather than forced into mutually exclusive categories.

Results

Neural Correlates of Language Proficiency

In relation to RQ1 regarding the correlation between neural oscillations and language proficiency, the reviewed studies have shown that individuals with higher language proficiency exhibit distinct brain wave activity (Ihara et al., 2021; Lizarazu et al., 2021; Prat et al, 2016, 2019). In contrast, individuals exhibiting low proficiency may primarily engage in fundamental or implicit cognitive processes (Ogunniyi et al., 2021), which are frequently characterized by the presence of theta brainwaves, suggesting a mode of learning characterized by experimentation and error correction. These findings link language proficiency to brainwave patterns, implying that language learning influences neural networks.

Resting-state EEG and qEEG indicate that intrinsic brain rhythms may provide a task-independent view into the neurocognitive foundations of language. The summary of the 19 research articles (see Appendix, Table A3) shows a dynamic system, not a single biomarker, where frequency bands, topography, and network properties reveal cognitive readiness, learning efficiency, and developmental stage. The findings are grouped into these core themes.

Theme 1: Spectral Power as a Predictor of Language Proficiency

A dominant finding across studies is that the absolute power within specific frequency bands during rest predicts an individual's capacity for language learning and their current proficiency level, especially reading skills. In terms of beta band activity, consistently higher resting-state power (13-30 Hz range) in the right hemisphere serves as a key neural marker for efficiency and proficiency in language-related tasks. Prat et al. (2016, 2019) found that neural predictors explain 60% of the variance in adult L2 learning rate, a result subsequently confirmed in older populations by Kliesch et al. (2021). Prat et al. (2016, 2019) showed that stable patterns of resting brain activity, captured by qEEG, are strong and consistent predictors of how well individuals learn a new language. In particular, findings showed positive correlations between low-beta power in the right hemisphere and L2 learning rates (r=0.60–0.77), and predicted 60% of the variation in final performance after eight weeks. Alvarez-Alonso et al. (2025) also reported increased frontal beta power in proficient vs.

struggling readers. Beta activity is linked to attention, information maintenance, and efficient processing, which are key for integrating novel linguistic input.

With regard to theta and delta band activity, these lower frequencies exhibit a complex, age-dependent relationship with cognitive load and language proficiency. In young children, higher resting power in the theta (4-7 Hz) and delta (1-3 Hz) ranges is predictive of better language skills, as shown by Zhang et al. (2025). This likely indicates domain-general processes like working memory and associative learning during early acquisition. Lum et al. (2022) linked higher resting theta power to weak sentence repetition, implying that this rhythm is linked to language maturation in children. Zhang et al. (2025) found that this effect is mediated by orthographic awareness. This association fades or reverses with age, due to skill automation and neural specialization via synaptic pruning (Zhang et al., 2025). Conversely, in adults and older learners, lower theta power and coherence are often linked to higher L2 proficiency, as indicated by Ogunniyi et al. (2021) and Prat et al. (2016), signifying a reduced reliance on effortful, working memory-based compensation. Across theoretical perspectives, theta oscillations consistently serve as a marker of processing load or cognitive cost (Lum et al., 2022). Higher proficiency is frequently associated with decreased theta coherence, implying that proficient individuals rely less on memory-based compensatory strategies (Ogunniyi et al., 2021).

In sum, these findings provide important insights into the neural architecture of reading proficiency and reinforce the significance of distributed brain networks in skilled reading. These results enhance our understanding of reading's neural substrates and underscore the importance of integrating multiple frequency bands and network measures in future investigations of cognitive processes related to reading proficiency.

Theme 2: The Crucial Role of Hemispheric Lateralization and Functional Connectivity

Beyond raw spectral power, the organization of neural networks, particularly in terms of lateralization and functional connectivity, emerges as a critical differentiator of proficiency and bilingual experience. A clear trend indicates that more lateralized resting-state patterns, especially within the alpha and right hemisphere beta frequency bands, are associated with faster L2 learning and higher proficiency, as demonstrated by Prat et al. (2016, 2019). This pattern is interpreted as a signature of a more specialized and efficient language network, reducing inter-hemispheric competition and aligning with the broader neural efficiency hypothesis.

Furthermore, research into connectivity reveals distinct resting-state profiles associated with bilingual experience. For instance, Bice et al. (2020) show that bilinguals exhibit enhanced alpha and beta band coherence compared to monolinguals, particularly within posterior and right-hemispheric networks. This heightened coherence is argued to reflect larger, more integrated neural assemblies that support the advanced language control and processing demands characteristic of managing multiple linguistic systems.

In terms of the predictability of L1 and L2, network properties may be more predictive of L1 than L2 skills. Lui et al. (2021) found that resting-state modularity correlated with L1 (Chinese) literacy but not L2 (English) reading, highlighting how L2 acquisition involves distinct, and potentially more variable, neural and cognitive resources, including affective factors.

Regarding the dominance of the right hemisphere in L2, multiple investigations underscore that right hemisphere (RH) activity, particularly within the beta and alpha bands, uniquely predicts second language (L2) learning rates and functional success. In contrast, left hemisphere (LH) activity is more conventionally associated with stabilized first language (L1) proficiency (Prat et al., 2016).

Theme 3: Age as a Fundamental Moderator

A critical synthesis reveals that age is not merely a covariate but a fundamental moderator of the relationship between oscillatory power and language skill. The neural substrates of language development shift in frequency prominence from infancy through adulthood. During early childhood, theta and delta power (Zhang et al., 2025) serve as primary correlates of language acquisition, linked to fundamental auditory processing, rapid associative learning, and working memory. As the brain develops into school age and adulthood, this predictive association gradually declines.

Additionally, a major methodological issue emerged from the analysis: resting-state EEG markers in children are inherently tied to neural maturation, complicating their interpretation, an important point emphasized by Kwok et al. (2019). As a result, it remains ambiguous whether the neural signatures observed represent lasting individual predictors or are instead simply transient products of a specific developmental period. To resolve this issue and separate maturational effects from true neural predictors of ability, longitudinal research designs are essential. As evidenced by the longitudinal approach of Zhang et al. (2025), repeated measurement of the same participants is necessary to determine which neural markers predict subsequent language and cognitive outcomes.

Theme 4: Bilingualism as a Neuromodulator

A growing body of research comparing monolinguals and bilinguals (Bice et al., 2020; Calvo et al., 2023; Soares et al., 2021) confirms that bilingual experience fundamentally shapes resting-state brain organization. This is evidenced by several neural signatures. Specifically, bilinguals often exhibit reduced theta power, increased alpha power, and enhanced alpha and beta coherence compared to monolinguals (Bice et al., 2020). However, Calvo et al. (2023) found similar alpha power across groups at rest and reported greater frontal beta coherence in monolinguals, a finding that contrasts with Bice et al.'s observation of heightened posterior alpha and beta connectivity in bilinguals during eyes-open conditions.

This apparent discrepancy may be reconciled by the Bilingual Anterior to Posterior and Subcortical Shift (BAPSS) model (Grundy et al., 2017), which describes a shift from frontal, effortful control to more posterior, automated processing as bilingual proficiency increases. According to this model, initial language acquisition relies heavily on domain-general frontal regions; however, with growing L2 proficiency, processing becomes more posterior and subcortical, reducing frontal resource demands as the language system becomes more efficient. These patterns align with the neural efficiency hypothesis, suggesting that bilinguals may employ more optimized neural mechanisms for attentional processes during rest.

Furthermore, bilinguals show altered reactivity, including reduced alpha reactivity (Calvo et al., 2023), which has been interpreted as a marker of neural efficiency. Overall, the bilingual brain is characterized by enhanced and reorganized coherence, demonstrating more robust long-range synchronization in higher frequency bands, a connectivity pattern that supports a functional network optimized for language management and switching.

The Four Perspectives of Proficiency

An analysis of the provided research uncovers a complex landscape in which language proficiency is operationalized through multiple lenses, including standardized academic testing, nuanced measures of social usage, and intrinsic neural readiness. The ensuing discussion synthesizes these findings across the four defined perspectives: linguistic, functional/communicative, cognitive/academic, and socio-cultural, in order to identify common themes and potential mismatches within the neurophysiological literature, thereby addressing RQ2.

We acknowledge that these perspectives are not mutually exclusive. For instance, DELE and TOEIC contain cognitive elements despite being primarily linguistic, and Prat

et al.'s (2016, 2019) virtual reality work spans both functional and socio-cultural dimensions, and we explicitly discuss such overlaps in the manuscript.

The Linguistic Perspective

The linguistic perspective, which emphasizes mastery of formal structures such as syntax and morphology, likewise constitutes a predominant framework (Ogunniyi et al., 2021; Zhang et al., 2025). Researchers frequently operationalize proficiency by examining the brain's response to linguistic violations through Grammaticality Judgment Tasks (GJT) (Ogunniyi et al., 2021). Proficiency is operationalized in reading studies through measures of orthographic awareness and phonemic deletion tasks, whereby neural power in the delta and theta bands predicts these specific linguistic sub-skills (Zhang et al., 2025).

A noticeable number of the language-related EEG studies reviewed adopt a primarily linguistic framework for conceptualizing language proficiency, emphasizing domains such as phonology, grammar, syntax, semantics, and vocabulary, while largely overlooking more encompassing functional or social dimensions. Although this approach has provided valuable insights into the neural underpinnings of core linguistic processes, it simultaneously reveals a notable gap in the existing literature concerning more comprehensive or ecologically grounded definitions of language proficiency. For instance, Kepinska et al. (2017) investigated the neural mechanisms of early grammar learning and individual differences. Two groups of participants (high vs. average language analytical ability) completed an Artificial Grammar Learning task while EEG was recorded. Behavioral results showed both learner groups improved their grammar learning performance, but the high language analytical ability (LAA) group significantly outperformed the moderate group.

Employing the LAMMA test, Kepinska et al. (2017) combined the cognitive perspective of language proficiency with the linguistic one. In another study, Papagiannopoulou and Lagopoulos (2016) aimed to examine resting-state (eyes-closed) EEG power spectra in pre-adolescent children with dyslexia compared to neurotypical controls, in order to identify neural abnormalities within the linguistic network. They used tests such as the Wechsler Abbreviated Scale of Intelligence (WASI-II, IQ >85), Dyslexia Early Screening Test (DEST) for children up to 6 years 5 months, and Dyslexia Screening Test-Junior (DST-J) for older children that evaluated rapid naming, phonological segmentation, reading, spelling, digit span, postural stability, vocabulary, and other domains. However, some subskills of the Wechsler Abbreviated Scale of Intelligence are in common with the cognitive perspective. These studies are uniformly confined to a linguistic perspective on language

proficiency, thereby overlooking the functional and socio-cultural dimensions of the construct. This predominant reliance on linguistic measures is similarly reflected in developmental research, where proficiency is frequently operationalized through standardized literacy assessments such as word reading and comprehension as measured by academic batteries including the PROLEC-SE-R5 (a standardized tool designed to evaluate lexical, syntactic, and semantic processes in reading (Alvarez-Alonso et al., 2025).

Beyond these formal structural assessments, an alternative line of inquiry has shifted focus toward the sensory and experiential dimensions of language processing, as exemplified by the emotioncy model. The emotioncy model operationalizes proficiency according to the quality of multisensory input; for instance, involvement via the five senses versus avolvement in the absence of any input. This conceptualization implies that linguistic proficiency is grounded in the richness of sensory experience, which subsequently modulates delta wave synchronization during L2 comprehension (Pishghadam et al., 2021).

Across the reviewed studies adopting a linguistic framework, evidence points toward the relevance of delta and theta oscillations, particularly in relation to orthographic awareness and phonemic deletion (Zhang et al., 2025). However, the extent to which other frequency bands, such as beta, contribute to linguistic proficiency remains less clear from the current synthesis, as the reviewed studies do not consistently report on these bands. Moreover, delta synchronization emerges during comprehension, modulated by the richness of sensory input, as proposed by the emotioncy model (Pishghadam et al., 2021).

The Functional/Communicative Perspective

A smaller but expanding group of studies takes a practical, communication-focused approach, looking at how well learners can use language to get things done (Prat et al., 2016, 2019). These studies often use exams like the TOEIC, which can evaluate communicative language ability in authentic contexts, to classify participants as either beginner or advanced (Emsawas et al., 2025). Standardized exams like IELTS, TOEFL, and TOEIC are often characterized by a hybrid design that balances the assessment of core linguistic skills with real-world communicative competence, thereby offering a more comprehensive evaluation of proficiency.

In recent years, a shift toward this functional/communicative operationalization has emerged, prioritizing learners' goal-directed language use over performance on grammar-based assessments. Prat et al. (2016, 2019) employed immersive virtual reality software in which proficiency was operationalized as the level attained in goal-directed scenarios. The

software employs a hierarchical organization centered on goal-based scenarios (e.g., obtaining transportation). It requires learners to interact with intelligent avatars through spoken language and the selection of socially relevant behaviors, including eye contact (or its absence), interruption of ongoing speech, and formality of intonation. Following each 30-minute training session, the participant's final level was documented. To derive a rate of second language (L2) acquisition, a regression line was fitted to the terminal-level data from each session, thereby enabling an investigation into the neurophysiological correlates of L2 learning rate. This paradigm shift departs from prescriptive grammar and instead emphasizes functional success in communication (Prat et al., 2016, 2019). Recent investigations have begun to quantify speech attempts and speaking accuracy during learning tasks as functional proxies for proficiency (Prat et al., 2019). These studies incorporated willingness to communicate (WTC) alongside speech attempts as measures of proficiency, revealing that such functional markers correlate with beta power in bilateral frontotemporal regions (Prat et al., 2019).

Synthesizing these findings, it becomes evident that under the functional/communicative perspective, proficiency is operationalized through goal-directed tasks, such as Prat et al.'s (2019) virtual immersion scenarios, which prioritize functional communication success over grammatical accuracy. However, the specific frequency bands (e.g., alpha or beta) and hemispheric laterality underlying these effects remain underexplored in the current synthesis.

The Cognitive/Academic Perspective

Across the past decade of EEG research, a dominant theme has been the consistent reliance on standardized, formal assessments to define proficiency groups. This operationalization aligns most closely with the cognitive/academic perspective, wherein language proficiency is viewed as a measurable score obtained from a high-stakes or institutionalized test. For instance, the DELE is employed to measure Spanish proficiency, and findings often indicate that neurophysiological markers, including theta coherence, correlate with these broad academic scores (Ogunniyi et al., 2021). Additionally, EIKEN CSE scores are applied to construct predictive models of listening proficiency (Ihara et al., 2021). EIKEN is one of the most widely used English-language testing programs in Japan. As mentioned previously, DELE and EIKEN are categorized under the linguistic perspective of language proficiency as well.

Beyond these standardized language tests, other studies have adopted a broader cognitive lens by incorporating assessments of general cognitive abilities such as executive

functioning, reasoning, and intelligence. Due to the evaluation of the L2 aptitude variable, executive functioning, Raven's Advanced Progressive Matrices (RAMP) in Prat et al. (2016, 2019), and verbal reasoning, attention, Wechsler Adult Intelligence Test in Alvarez-Alonso et al. (2025), and assessing Raven's non-verbal intelligence test (Raven's Standard Progressive Matrices) in Zhang et al. (2025), they have a cognitive lens toward language proficiency.

Critically, these cognitive assessments are not employed in isolation; rather, they are frequently examined in relation to neural oscillatory activity. Alvarez-Alonso et al. (2025), for example, link neural markers such as beta power and network modularity to academic outcomes like word reading and comprehension. Extending this line of inquiry beyond concurrent associations, a considerable portion of the literature (Bice et al., 2020; Kliesch et al., 2021; Prat et al., 2016) conceptualizes proficiency as a potential aptitude or neurobiological fingerprint. Within this framework, resting-state EEG, specifically beta power recorded over the right hemisphere, is applied to forecast the rate of subsequent learning, thereby implying that proficiency is understood as the brain's intrinsic baseline efficiency or readiness to assimilate new linguistic information (Prat et al., 2016). This prominent line of inquiry regards proficiency as an outcome of neurobiological readiness (Elmer et al., 2023).

Complementing these aptitude-based approaches, longitudinal developmental studies have further explored how resting-state EEG dynamics evolve with age and contribute to vocabulary acquisition over time. Meng et al. (2022) aimed to investigate how developmental changes in resting-state EEG power relate to vocabulary acquisition in Chinese school-age children. Specifically, the researchers examined longitudinal changes in brain rhythms from ages 7 to 11 and explored the mediating mechanisms (e.g., phonological processing) that might explain the link between brain rhythm maturation and vocabulary knowledge. Children completed a battery of behavioral measures at each time point, including non-verbal IQ (Raven's matrices), working memory (backward digit span), phoneme deletion, tone and pitch discrimination, rapid automatized naming (RAN), expressive vocabulary (vocabulary definition subtest from the WISC-CR), and receptive vocabulary (adapted Peabody Picture Vocabulary Test, PPVT).

Across these diverse methodological approaches, a consistent pattern emerges in the association between neural oscillations and the cognitive/academic perspective. Across studies, theta and beta oscillations consistently predict academic language outcomes: Theta coherence correlates with standardized academic test scores, such as the DELE (Ogunniyi et al., 2021). Furthermore, lower theta power is associated with better reading performance

and vocabulary scores in Chinese children (Meng et al., 2022; Zhang et al., 2025). Beta-band power consistently correlates positively with both language proficiency and learning rate. Right-hemisphere beta power predicts learning rate (Prat et al., 2016), as well as reading and comprehension skills as measured by academic batteries (Alvarez-Alonso et al., 2025). In adult L2 learners, higher RH posterior beta power predicts faster acquisition (Prat et al., 2016, 2019), and skilled readers likewise show greater frontal beta power than less proficient ones. In children, greater beta power gains between ages 7 and 9 similarly predict better receptive vocabulary at age 11 (Meng et al., 2022). In contrast, alpha power shows a more nuanced pattern; high-proficiency readers display slightly lower alpha peak power, yet greater alpha laterality (higher RH than LH power) positively predicts L2 learning rates in adults (Prat et al., 2019).

The Socio-Cultural Perspective

In recent neurophysiological research, the socio-cultural perspective repositions language not as a set of internal mental rules but as a multidimensional construct embedded in social environments. To capture this perspective, researchers have combined EEG measurements with validated questionnaires that assess the quality and quantity of language exposure, socioeconomic factors, and the specific contexts in which dual-language use occurs. For example, Soares et al. (2021) and Calvo et al. (2023) used the Language and Social Background Questionnaire (LSBQ) as a tool that moves beyond binary "monolingual vs. bilingual" classifications. The instrument computes factor scores across three dimensions: Home (non-societal language use within the family), Social (language use in community or social settings), and proficiency in the societal language. In addition, Bice et al. (2020) employed the Language Experience and Proficiency Questionnaire (LEAP-Q), which assesses language history, age of acquisition, and current usage proportions. Furthermore, Meng et al. (2022) and Soares et al. (2021) used socioeconomic status (SES) measures, including parental education (often specifically maternal education) and household income, to characterize the family environment.

Synthesizing these diverse operationalizations, a consistent pattern emerges regarding the association between the socio-cultural perspective and neural oscillations. That is, this review reveals that specific social factors serve as potent neuromodulators, shaping the brain's resting-state organization. According to Soares et al. (2021), greater social engagement with a minority language significantly altered functional connectivity. In particular, more frequent social use predicted stronger theta-band synchrony between frontal

and frontotemporal areas, an effect thought to stem from the high inhibitory demands of navigating between two languages. On the basis of Meng et al. (2022), maternal education predicted delta power at age 9, pointing to SES as a key factor in the developmental course of brain rhythms. Soares et al. (2021) revealed that posterior alpha coherence was modulated by home-based exposure to a non-societal language, which acted as an indicator of bilingual usage intensity in the private sphere.

Beyond these broader social and environmental factors, specific patterns of language use, particularly the timing and intensity of L2 exposure, have also been shown to shape neural oscillations in distinct ways. Bice et al. (2020) reported that higher alpha power correlated with both earlier L2 age of acquisition and a larger share of current L2 use. According to their account, the prolonged, repeated management of two languages in multiple social contexts calibrates alpha activity, an effect evident even at rest, as a neural index of language control. According to Calvo et al. (2023), bilingualism operates as socially acquired expertise, wherein the extent of experience drives neural efficiency. This is evidenced by diminished alpha reactivity across the scalp and more focused interhemispheric interactions in posterior areas when attention is required.

In conclusion, the socio-cultural perspective confirms that neural biomarkers are context-dependent, not fixed. Variables like home literacy environment, maternal education, and engagement in minority language communities offer a nuanced neurobiological indicator of language readiness. Together, these findings imply that resting-state EEG reflects the cumulative influence of social experiences on the brain's linguistic preparedness.

Conclusion

As for the first research question, resting brain rhythms appear to be a useful tool for probing language-related neural function. Right-hemisphere beta activity consistently predicts better language learning and skill, interpreted as a marker of attention and efficiency. In contrast, theta/delta activity shows a clear age interaction, benefiting children through domain-general resources, but inversely relating to adult proficiency, where lower power reflects automaticity. In addition, network organization is equally critical; alpha/beta lateralization marks language specialization, while bilingualism boosts high-frequency coherence and reduces low-frequency reactivity, signaling optimized control. Crucially, resting EEG predictors shift across life, from low-frequency learning correlates in childhood to high-frequency efficiency markers in adulthood, all shaped by cumulative language experience.

Collectively, the studies show that EEG biomarkers are context-dependent rather than fixed, varying with age, experience, and study design.

Regarding the second research question, the findings reveal a clear imbalance in how language proficiency has been operationalized across EEG studies. The linguistic and cognitive/academic perspectives dominate the literature, with the majority of studies employing formal structural measures such as grammaticality judgment tasks, orthographic awareness tests, and standardized academic assessments like DELE, EIKEN, and PROLEC-SE-R (Alvarez-Alonso et al., 2025; Ogunniyi et al., 2021; Zhang et al., 2025), alongside cognitive ability measures including working memory, executive functioning, and nonverbal reasoning (Meng et al., 2022; Prat et al., 2016, 2019). In contrast, the functional/communicative perspective, while gaining traction through immersive virtual reality paradigms that prioritize goal-directed communication success over grammatical accuracy (Prat et al., 2016, 2019), remains comparatively underrepresented. The socio-cultural perspective is even less prevalent, appearing primarily in studies that supplement EEG measurements with questionnaires such as the LSBQ and LEAP-Q to capture language exposure, use patterns, and socioeconomic factors (Soares et al., 2021; Bice et al., 2020; Calvo et al., 2023). This theoretical imbalance suggests that while neural oscillations robustly correlate with proficiency as defined by formal and cognitive metrics, the field has yet to fully explore how EEG markers align with more ecologically grounded, socially embedded conceptualizations of language ability, highlighting a critical gap for future investigation.

The literature's inconsistencies stem from several factors, including narrow cognitive-linguistic definitions of proficiency that exclude functional and socio-cultural dimensions, age-related reversals (where patterns beneficial in children may indicate inefficiency in adults), population differences (monolingual vs. bilingual, L1 vs. L2), and methodological variation in regions, bands, and metrics. Compounding these conceptual and methodological issues is the observation that, despite searching multiple databases for 2015–2025 studies, we found a heavy emphasis on reading skills at the expense of other proficiency domains. Similarly, our keyword strategy, including skill-based and broader terms, may still have biased retrieval toward cognitive-linguistic frameworks. Beyond retrieval bias, inconsistent operationalization of proficiency, bilingualism, and resting-state protocols further hinders comparability across studies. In addition to these conceptual and procedural concerns, this systematic review is subject to additional practical limitations, including lack of PROSPERO registration (due to the review being conducted as part of a dissertation with time constraints that precluded the registration process), small sample sizes of the included studies, language

bias resulting from the restriction to English-language articles, publication bias due to the exclusion of certain literature, and a lack of consideration for variability in resting-state protocols, such as eyes-open versus eyes-closed conditions. Also absent from the discussion are the practical barriers of EEG (cost, training, time), administrator accountability, and result translation for educators.

Beyond these general limitations, a more specific and unresolved challenge concerns the alpha enigma, the inconsistent and often contradictory role of alpha oscillations (8–12 Hz) in predicting language proficiency. While Ogunniyi et al. (2021) and Bice et al. (2020) link higher alpha power to better skills and inhibitory control, Álvarez-Alonso et al. (2025) and Kwok et al. (2019) show non-significant or opposing trends. This ambiguous polarity is influenced by scalp topography, age, and analytic parameters, which prevent alpha activity from serving as a universal neural signature for proficiency. To clarify these discrepancies, we attribute alpha-band polarity differences in this synthesis to three interacting factors: developmental stage (maturational in children vs. efficiency in adults), topographic specificity (posterior vs. frontal), and analytic choices (absolute vs. relative power, peak vs. broadband measures, eyes-open vs. eyes-closed baselines). Considering these jointly resolves apparent contradictions, highlighting alpha as a context-sensitive index of inhibition and timing rather than a fixed proficiency marker. Given these complexities, future work should report individual alpha frequency, topography, and protocol details to improve cross-study comparability and should expand search terms to include socio-cultural and communicative competence for more balanced coverage.

It is worth noticing, however, that resting-state EEG correlates with linguistic abilities but does not measure proficiency directly. Any links to reading, vocabulary, phonological processing, working memory, or L2 skill remain correlational, not causal, and that distinction matters. Due to practical barriers to EEG implementation, including cost, equipment, and expertise, EEG-based L2 assessment remains primarily a research tool rather than a classroom-ready solution. Rather than proposing EEG as a near-term complement to objective proficiency tests, which is not a limitation unique to our study, we suggest that current findings primarily inform theoretical models of the neurocognitive underpinnings of language proficiency, while any assessment-oriented use remains speculative and contingent upon significant technological, financial, and ethical advancements. For educators, this implies that behavioral observation of student engagement and performance remains the most practical approach to classroom assessment at present.

To resolve these inconsistencies, future work should prioritize longitudinal training study designs that track how resting rhythms shift with age and growing expertise, rather than relying on comparisons. At the same time, causal accounts of bilingual restructuring call for experimental approaches such as longitudinal training studies, repeated measurement of the same participants, and intervention studies. Advancing the field will also mean moving toward multivariate frameworks that combine power, connectivity, and lateralization measures for more stable prediction. Equally important are methodological standardization and replication across diverse populations to ensure reliable, comparable findings. Furthermore, the application of machine learning to EEG data for proficiency classification holds considerable potential and warrants further investigation in future research. Last but not least, building on the neurocognitive evidence reviewed here, Pishghadam's (2026) magnitude research framework may offer a complementary lens for evaluating complex, multi-level outcomes by emphasizing scale, impact, complexity, holism, and accuracy, which could inform future interdisciplinary investigations of language proficiency that bridge neuroscience, education, and organizational contexts.

Declaration of Conflicting Interests

The authors do not have any conflicts of interest to declare.

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AI Use Statement

The authors acknowledge that artificial intelligence tools were employed exclusively for language polishing and copyediting purposes. All substantive content, analyses, and interpretations are the sole responsibility of the authors.

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Appendices

Table A1. PRISMA Checklist

Section/topic	#	Checklist item	Reported on section #
TITLE			
Title	1	EEG Correlates of Language Proficiency: A Systematic Review with Theoretical Analysis	First Page
ABSTRACT			
Structured summary	2	Provide a structured summary including, as applicable: background; objectives; data sources; study eligibility criteria, participants, and interventions; study appraisal and synthesis methods; results; limitations; conclusions and implications of key findings; systematic review registration number.	Abstract
INTRODUCTION			
Rationale	3	Describe the rationale for the review in the context of what is already known.	Introduction
Objectives	4	Provide an explicit statement of questions being addressed with reference to participants, interventions, comparisons, outcomes, and study design (PICOS).	Introduction
METHODS			
Protocol and registration	5	Indicate if a review protocol exists, if and where it can be accessed (e.g., Web address), and, if available, provide registration information, including registration number.	Method
Eligibility criteria	6	Specify study characteristics (e.g., PICOS, length of follow-up) and report characteristics (e.g., years considered, language, publication status) used as criteria for eligibility, giving rationale.	Method (Section 3.3.)
Information sources	7	Describe all information sources (e.g., databases with dates of coverage, contact with study authors to identify additional studies) in the search and the date last searched.	Method

Section/topic	#	Checklist item	Reported on section #
Search	8	Present a full electronic search strategy for at least one database, including any limits used, such that it could be repeated.	Method
Study selection	9	State the process for selecting studies (i.e., screening, eligibility, included in the systematic review, and, if applicable, included in the meta-analysis).	Method
Data collection process	10	Describe the method of data extraction from reports (e.g., piloted forms, independently, in duplicate) and any processes for obtaining and confirming data from investigators.	Method (Section 3.3) and Figure 1
Data items	11	List and define all variables for which data were sought (e.g., PICOS, funding sources) and any assumptions and simplifications made.	Method
Risk of bias in individual studies	12	Describe methods used for assessing risk of bias of individual studies (including specification of whether this was done at the study or outcome level), and how this information is to be used in any data synthesis.	Table A2
Summary measures	13	State the principal summary measures (e.g., risk ratio, difference in means).	Table A3
Synthesis of results	14	Describe the methods of handling data and combining results of studies, if done, including measures of consistency (e.g., I2) for each meta-analysis.	-
Risk of bias across studies	15	Specify any assessment of risk of bias that may affect the cumulative evidence (e.g., publication bias, selective reporting within studies).	Table A2
Additional analyses	16	Describe methods of additional analyses (e.g., sensitivity or subgroup analyses, meta-regression), if done, indicating which were pre-specified.	-
RESULTS			
Study selection	17	Give the number of studies screened, assessed for eligibility, and included in the review, with reasons for exclusions at each stage, ideally with a flow diagram.	Method (Section 3.3) and Figure 1

Section/topic	#	Checklist item	Reported on section #
Study characteristics	18	For each study, present characteristics for which data were extracted (e.g., study size, PICOS, follow-up period) and provide the citations.	Table A3
Risk of bias within studies	19	Present data on the risk of bias of each study and, if available, any outcome-level assessment.	Table A2
Results of individual studies	20	For all outcomes considered (benefits or harms), present, for each study: (a) simple summary data for each intervention group (b) effect estimates and confidence intervals, ideally with a forest plot.	Table A3
Synthesis of results	21	Present results of each meta-analysis done, including confidence intervals and measures of consistency.	Table A3
Risk of bias across studies	22	Present results of any assessment of risk of bias across studies.	Table A2
Additional analysis	23	Give results of additional analyses, if done (e.g., sensitivity or subgroup analyses, meta-regression).	-
DISCUSSION			
Summary of evidence	24	Summarize the main findings, including the strength of evidence for each main outcome; consider their relevance to key groups (e.g., healthcare providers, users, and policy makers).	Conclusion and Implications
Limitations	25	Discuss limitations at the study and outcome level (e.g., risk of bias), and at the review level (e.g., incomplete retrieval of identified research, reporting bias).	Conclusion and Implications
Conclusions	26	Provide a general interpretation of the results in the context of other evidence and implications for future research.	Conclusion and Implications
FUNDING			
Funding	27	Describe sources of funding for the systematic review and other support (e.g., supply of data); role of funders for the systematic review.	Funding

Table A2. Results of Risk of Bias Assessment

Article	Instrument used	Score	Quality
Zhang et al. (2025)	JBI Critical Appraisal Checklist for Cohort Studies	8/9	high
Emsawas et al. (2025)	JBI Critical Appraisal Checklist for Analytical Cross-Sectional Studies	7/8	high
Alvarez-Alonso et al. (2025)	JBI Critical Appraisal Checklist for Analytical Cross-Sectional Studies	6/8	moderate
Ihara et al. (2021)	JBI Critical Appraisal Checklist for Analytical Cross-Sectional Studies	8/8	high
Elmer et al. (2023)	JBI Critical Appraisal Checklist for Quasi-Experimental Studies	7/9	high
Calvo et al. (2023)	JBI Critical Appraisal Checklist for Analytical Cross-Sectional Studies	7/8	high
Lum et al. (2022)	JBI Critical Appraisal Checklist for Analytical Cross-Sectional Studies	7/8	high
Lui et al. (2021)	JBI Critical Appraisal Checklist for Analytical Cross-Sectional Studies	7/8	high
Ogunniyi et al. (2021)	JBI Critical Appraisal Checklist for Analytical Cross-Sectional Studies	6/8	moderate
Kliesch et al. (2021)	JBI Critical Appraisal Checklist for Quasi-Experimental Studies	8/9	high
Soares et al. (2021)	JBI Critical Appraisal Checklist for Analytical Cross-Sectional Studies	7/8	high
Zhou et al. (2020)	JBI Critical Appraisal Checklist for Analytical Cross-Sectional Studies	6/8	moderate
Bice et al. (2020)	JBI Critical Appraisal Checklist for Analytical Cross-Sectional Studies	7/8	high
Prat et al. (2019)	JBI Critical Appraisal Checklist for Quasi-Experimental Studies	7/9	moderate
Prat et al. (2016)	JBI Critical Appraisal Checklist for Quasi-Experimental Studies	6/9	moderate
Pishghadam et al. (2021)	JBI Critical Appraisal Checklist for Quasi-Experimental Studies	7/8	high
Papagiannopoulou and Lagopoulos (2016)	JBI Critical Appraisal Checklist for Analytical Cross-Sectional Studies	7/8	high
Meng et al. (2022)	JBI Critical Appraisal Checklist for Cohort Studies	8/9	high
Kepinska et al. (2017)	JBI Critical Appraisal Checklist for Quasi-Experimental Studies	9/9	high

Table A3. Summary of the 19 Research Articles

	Author(s) & Year, Title	Sample Size & Population	Study design/Task Type	EEG Measurements (Electrode Count)	Key Findings	Limitations
1.	Zhang et al. (2025), Electrophysiological activity predicts children's reading ability through orthographic awareness: Evidence from a cross-sectional and longitudinal study	73 right-handed native Chinese children from Grades 2–6	Resting state EEG, ERP, Cross-sectional and Longitudinal study, Non-verbal intelligence, the standardized Raven's Progressive Matrice, orthographic awareness	32-channel Ag/AgCl cap according to the international 10–20 system, band-pass filter: 0.1–100 Hz, Data were resampled at 500 Hz. Independent Component Analysis (ICA) was used to manually identify and remove artifacts. Confidence intervals: 95%	• Delta and theta brain waves primarily impacted reading ability indirectly by influencing orthographic awareness, not through direct effects. • The influence of these brain rhythms on reading and word recognition was strongest in younger children and weakened or changed as they grew older. • An exception was that delta power at the initial time point (T1) did have a direct effect on reading ability.	• Small sample size per grade • Short longitudinal duration • Including participants across a wide age spectrum (7–13 years) resulted in developmental variability, complicating the identification of specific age-related patterns. • Absence of intervention data and restriction to observation rather than investigating the potential effects of particular teaching practices
2.	Emsawas et al. (2025), Identifying English proficiency by frontal theta activity during English learning	52 native Japanese-speaking adults (20–48 years)	EEG, cross-sectional group comparison, before-lesson Session (Resting-state), during-lesson Session (Learning Task), after-lesson Session (Recovery)	Eight electrode positions: Fp1, Fp2, F7, F3, F4, F8, T7, and T8, (10–20 System), The reference electrode: Fz, ground electrode: Fpz, band-pass filter: 0.5–100 Hz, moderate effect size f=0.20	• Advanced students demonstrated greater frontal theta activity than beginners during the English lesson. • This pattern indicates that advanced students exert more focused attention during L2 learning, which correlates with their skill level.	• Equipment cost and complexity • The EEG headset itself may alter cognitive activity, potentially reducing ecological validity compared to real-world contexts. • The study limited its investigation to concentration (frontal theta) and did not account for other L2 learning factors, such as affective or emotional states.
3.	Alvarez-Alonso et al. (2025), An exploratory EEG comparison of good and bad readers	18 participants (9 good readers and 9 poor readers)	Cross-sectional group comparison design, 5-minute resting state EEG (eyes closed), WAIS-IV (Wechsler Adult Intelligence	64-channel Ag/AgCl cap according to the international 10–20 system, Artifacts signals were removed by the OHBA Software	• Compared to poor readers, good readers demonstrated significantly greater beta power in frontal areas and	• Small Sample Size • The cross-sectional design prevents longitudinal tracking of neural changes in literacy development. • The correlational

	Author(s) & Year, Title	Sample Size & Population	Study design/Task Type	EEG Measurements (Electrode Count)	Key Findings	Limitations
			Scale), and the PROLEC-SE-R Reading Process Assessment Battery	Library (OSL), Band-pass filtering (2–45 Hz) was performed with 2-second padding.	stronger functional connectivity in fronto-central-parietal networks. • The elevated beta activity observed in proficient readers aligns with its established functions in top-down cognitive control and linguistic processing.	design prevents causal inferences about neural oscillations and reading.
4.	Ihara et al. (2021), Prediction of second language proficiency based on electroencephalographic signals measured while listening to natural speech	Two hundred and five adult monolingual native Japanese Speakers (20–39 years)	Cross-sectional, predictive modeling design, Natural Speech Listening Task (EEG Session), Comprehension Monitoring Task, EIKEN	Eight-channel wireless EEG device, Active EEG electrodes were placed at Fz, Cz, Pz, FC5, and FC6 (10-10 system), with additional EOG channels, bandpass FIR filter: 0.5–50 Hz. Confidence intervals: 95%	• Results showed significant negative associations between listening scores and EEG features. • The study suggested that, based on neural signatures measured while listening to natural sound, L2 ability can be assessed.	• The absence of a native English comparison group limits interpretation of the neural findings. • Educational background data were not collected, potentially affecting the results. • EEG technology is expensive, complex, and requires specialized training, making it less practical for widespread use than paper-based tests.
5.	Elmer et al. (2023), Foreign speech sound discrimination and associative word learning lead to a fast reconfiguration of resting-state networks	40 subjects (mean age = 25.47 years)	EEG, pre-post task comparison design, word repetition detection, and a word discrimination task, a 3-minute eyes-closed resting-state task	32 active Ag/Cl electrodes (10-20 system), bandpass filter of 0.1–30 Hz (48 dB/oct), and a 50 Hz Notch filter were applied.	• Increased activity in the brain's theta and upper alpha waves was linked to a reduced ability to apply word meanings to similar concepts. • The way the brain's upper alpha rhythm changed could predict a person's skill in telling words apart. • Theta brain waves are linked to encoding new	• The functional interpretation of resting-state rhythms remains ambiguous, making it difficult to link EEG measures to specific cognitive functions. • The correlation analyses produced lower explained variance than previous comparable studies.

	Author(s) & Year, Title	Sample Size & Population	Study design/Task Type	EEG Measurements (Electrode Count)	Key Findings	Limitations
					memories and consolidating them via hippocampal-neocortical interactions.	
6.	Calvo et al. (2023), Bilingualism modulates neural efficiency at rest through alpha reactivity	25 bilingual and 25 monolingual young adult participants	Cross-sectional group comparison, EEG, eyes-open resting state (3 minutes), eyes-closed resting state (3 minutes) , employing LSBQ to determine the degree and duration of bilingual experience	64-channel Biosemi Active Two system (10–20 system), A bandpass filter of 0.5–50 Hz was applied, All procedures complied with university ethics guidelines, ICA was used to detect and correct eye movements and blinks.	• Alpha power patterns are similar across groups, but bilinguals exhibit reduced alpha reactivity globally. • Frontal alpha and beta connectivity is generally lower in bilinguals compared to monolinguals. • During the attentive, eyes-open state, bilinguals show greater posterior alpha and beta connectivity.	• The undergraduate psychology sample may limit generalizability to other age groups or non-university populations. • Small sample size • The study reduces bilingualism to a binary comparison (monolingual vs. bilingual), despite acknowledging its complexity and the wide range of linguistic experiences that exist along the continuum.
7.	Lum et al. (2022), Resting state electroencephalography (EEG) correlates with children's language skills: Evidence from sentence repetition	52 English-speaking children (9-11)	cross-sectional, correlational design, 2-minute resting state EEG (eyes open), sentence repetition task, Matrix Reasoning Task	64-channel high-impedance Geodesic Sensor Net system, Cz was used as the online reference, A 0.5 Hz high-pass, 50 Hz notch, and 80 Hz low-pass filter were applied.	• Higher resting theta power was linked to poorer performance on a sentence repetition task. • Findings suggest that theta reflects the maturation of language skills in children.	• The cross-sectional design underscores the need for longitudinal or larger-scale cross-sectional studies (infancy to late childhood) to confirm developmental changes in brain-language associations. • The Recalling Sentences subtest lacks systematic manipulation of sentence length, word frequency, and syntactic complexity. • Therefore, the exact neural correlates of resting-state theta for language remain undetermined.

	Author(s) & Year, Title	Sample Size & Population	Study design/Task Type	EEG Measurements (Electrode Count)	Key Findings	Limitations
8.	Lui et al. (2021), Resting state EEG network modularity predicts literacy skills in L1 Chinese but not in L2 English	90 children (6-12 years)	Cross-sectional, correlational design, Eyes-open resting-state EEG task (3 minutes), behavioral literacy tasks (L1 Chinese), behavioral literacy tasks (L2 English), Nonverbal IQ (NVIQ): Raven's Standard Progressive Matrices, Verbal Working Memory (WM): digit span test	HydroCel GSN EGI 128-channel system, Cz was used as online reference, A 0.1 Hz high-pass filter was used during acquisition, and a 40 Hz low-pass filter during preprocessing	• Resting-state EEG modularity positively correlated with Chinese literacy skills but not English abilities, indicating its potential as a cost-effective neural biomarker for first-language development. • Findings posit resting-state EEG network modularity as a specific neural marker for first-language, but not second-language, literacy skill development.	• Lack of Causal Evidence • The cross-sectional design limits understanding of developmental change; longitudinal studies are needed to examine how these relationships evolve over time. • Language measures were imbalanced, with fewer English than Chinese reading tests. Crucially, phonological awareness and reading comprehension, the strongest Chinese predictors, were not assessed in English.
9.	Ogunniyi et al. (2021), Neural oscillations as predictors of variability in second language proficiency	49 participants (18-38)	Cross-sectional, Exploratory study (pairwise correlations followed by simultaneous linear regression models), five minutes of eyes-closed resting state EEG task, grammaticality judgement task, DELE, Language Experience and Proficiency Questionnaire (LEAP-Q)	32 Ag/AgCl electrodes in an ANT Neuro waveguard™ elastic cap (10-20 system), a common average reference was applied online, using the mean signal across all scalp electrodes. A 138.24 Hz low-pass filter was applied online. Preprocessing was conducted using EEGLab (MATLAB).	• Negative correlation between theta frequency coherence and the DELE (L2 proficiency test) • Positive correlation between medial frontal alpha power and DELE scores • Positive correlation between left hemisphere frontotemporal alpha power and DELE scores.	• The DELE and grammaticality judgment task focus mainly on prescriptive grammar and do not assess broader proficiency components like oral communication. • Automated artifact cleaning excluded 12% of participants (n = 6); the authors recommend using ICA for more effective artifact removal in future studies. • Including students from two semester levels (third and fourth) may have introduced unwanted variability.
10.	Kliesch et al. (2021), EEG resting-state and event-related potentials as markers of learning success in older adults following	Ten healthy older participants (65–73 years)	Longitudinal, experimental design, resting state EEG task (both eyes open and eyes closed),	High-resolution system with 128 Ag/AgCl electrodes. Data were collected using the BioSemi	• Pre-training resting-state beta1 power reliably predicted the rate of a person's second	• Longer, denser longitudinal studies are required to track individual learning trajectories. • Small sample size

	Author(s) & Year, Title	Sample Size & Population	Study design/Task Type	EEG Measurements (Electrode Count)	Key Findings	Limitations
	second language training: A pilot study		C-Test, listening comprehension task, ERP language-switching task	ActiveTwo system. Independent Component Analysis (ICA) was used for artifact correction. Offline filters were set at 0.1 Hz (low cutoff) and 30 Hz (high cutoff).	language (L2) learning progress. • Individuals with higher beta1 power before training showed greater improvement in their second language skills.	• Without a younger or age-matched control group, it is unclear whether the findings reflect aging, experience, or language learning per se. • Comparing only pre- and post-training data ignored the learning process in between.
11.	Soares et al. (2021), Determinants of bilingualism predict dynamic changes in resting state EEG oscillations	103 bilingual participants (Mean Age = 28.34)	Cross-sectional, individual differences design, 5-minute resting state EEG (eyes closed), Language and Social Background Questionnaire (LSBQ)	32 active Ag/AgCl scalp electrodes using the Brain Products LiveAmp32 system, FCz served as the online reference, A ground electrode was positioned at AFz. Band-pass filtering (0.1–45 Hz) was applied, with a 1 Hz low-cut used for 11 participants to reduce sweat artifacts.	• Positive correlation between theta coherence and frequent use of the non-societal language • Positive correlation between theta coherence in frontal regions and proficiency in societal language • Positive correlation between proficiency and alpha coherence between frontal left and right clusters and Medial frontal.	• The uniformly high self-reported proficiency and limited score range may explain why proficiency did not significantly modulate alpha power. • Because a 1 Hz filter was used for some participants, delta band analysis was not feasible due to compromised data reliability.
12.	Zhou et al. (2020), Monitoring of attentional oscillations through spectral similarity analysis predicts reading comprehension	67 English monolingual speakers (18 - 33 years)	Cross-sectional study, correlational study, EEG, 5-minute eyes-closed resting-state EEG, further 5-minute EEG during a reading comprehension task, reading comprehension task, Simon task, and (LEAP-Q)	Wireless 16-channel headset (Emotiv EPOC), 14 active channels: AF3, AF4, F3, F4, FC5, FC6, F7, F8, T7, T8, P7, P8, O1, and O2, Reference channels were DMS and CRL (parietal lobe). Continuous EEG was sampled at 128 Hz.	• A higher frequency of attentional shifts recorded over the left occipital region (O1) was inversely correlated with reading comprehension performance. • The proportion of attentional shifts over the left visual cortex served as a significant negative	• The 16-channel wireless headset limited data quality; a higher-density EEG would cover the whole scalp rather than primarily posterior regions. • Spectral Similarity Analysis (SSA) cannot differentiate between attentional shifts caused by task-related retrieval versus irrelevant distractions. Both generate similar spectral patterns,

	Author(s) & Year, Title	Sample Size & Population	Study design/Task Type	EEG Measurements (Electrode Count)	Key Findings	Limitations
					predictor for reading test performance.	making it unclear which cognitive state is being captured.
13.	Bice et al. (2020), Bilingual language experience shapes resting-state brain rhythms	96 monolingual speakers and 106 bilingual speakers (18-35)	Cross-sectional group comparison, 5-minute EEG resting state (EC), Simon task, LEAP-Q	Wireless 16-channel Emotiv headset, 14 scalp electrodes (AF3, AF4, F3, F4, F7, F8, FC5, FC6, T7, T8, P7, P8, O1, O2), The reference scheme consisted of CMS and DRL electrodes. Confidence intervals: 95%	• Bilinguals show greater alpha power in posterior & medial frontal regions, higher beta/gamma power and coherence in right posterior areas, and lower theta power in left frontotemporal areas. • Increased right-hemisphere beta activity at rest predicts faster language learning. • Alpha frequency increases with more L2 use, higher L1 proficiency, and earlier L2 acquisition.	• The heterogeneous bilingual sample is both a strength and a limitation: it increases generalizability but may have masked specific effects due to wide variability in language history. • Most bilinguals (96%) were L2-immersed, and 64% had shifted dominance to English (L1). The implications of such a switch are unknown, and results may vary across linguistic contexts. • A major limitation is the use of self-reported proficiency; future studies should adopt more objective measures.
14.	Prat et al. (2019), Individual differences in resting-state brain rhythms uniquely predict second language learning rate and willingness to communicate in adults	41 healthy monolingual English adults (18–34 years) with no prior French exposure	Longitudinal, individual differences approach, quasi-experimental, 5-minute resting-state EEG Task (EC), Raven's Advanced Progressive Matrices (RAPM), Simon task, Nelson–Denny Reading Test (NDRT), sixteen 30-minute sessions of French, Language Training Task	Wireless, 16-channel Emotiv EPOC headset, Reference channels were DMS and CRL. A 5-minute eyes-closed resting-state EEG was recorded at 128 Hz. Electrodes were: (AF3, AF4, F3, F4, F7, FC5, T7, F8, FC6, T8, P7, O1, (P8, O2).	• Right hemisphere (RH) dominance predicts faster learning. • Key L2 predictors: RH posterior beta & frontotemporal alpha laterality • L1 proficiency links to posterior alpha & frontal theta. • Reduced left hemisphere (LH) posterior coherence aids L2 learning rate.	• The 8-week L2 exposure, though standard in aptitude research, may be too short for learners to reach the ultimate level of proficiency. • The use of a specific virtual immersion software raises questions about whether the findings generalize to traditional classrooms or natural immersion contexts. • Whether these neural predictors are language-specific or represent a general learning ability remains unresolved.

	Author(s) & Year, Title	Sample Size & Population	Study design/Task Type	EEG Measurements (Electrode Count)	Key Findings	Limitations
15.	Prat et al. (2016), Resting-state qEEG predicts rate of second language learning in adults	16 adults (18–31 years)	Longitudinal, individual differences approach, quasi-experimental, 5-minute resting-state EEG task, Raven's Advanced Progressive Matrices (RAPM), Simon task, Nelson–Denny Reading Test (NDRT), translation test, sixteen 30-minute sessions of French, Language Training Task	Wireless, 16-channel Emotiv EPOC headset, Reference channels were DMS and CRL. 5-minute eyes-closed resting-state EEG was recorded at 128 Hz. Data were epoched into 2-second intervals with a 50% overlap (1 second). Hanning window was applied to each epoch to minimize spectral leakage.	• Positive correlation between power in beta and low-gamma frequency and second language acquisition (SLA) over right temporoparietal regions was observed. • Data revealed a negative correlation between power in the theta frequency band and L2 learning rate in the left parietal lobe (P7) • A positive correlation between mid-beta, high-beta, low-gamma, and L2 learning rate was observed.	• Small sample size: non-significant correlations between cognitive measures and learning rates stem from the small sample size. • Dominance of the female sample (75%) may limit the generalizability of these qEEG findings. • Training consisted of only eight hours across 16 sessions, a relatively brief exposure. • The study measured learning rate (speed through levels) but ignored skill quality (depth of learning).
16.	Pishghadam et al. (2021), Oscillatory neuronal dynamics during L2 sentence comprehension: the effects of sensory enrichment and semantic incongruency	22 subjects (between 18 and 30 years)	Experimental, within-subjects design, the emotioncy scale, Oxford quick placement test, digit span, Edinburgh handedness inventory, sensory enrichment (learning session), visual sentence acceptability judgment task (with EEG)	23 active Ag/AgCl sintered electrodes (10-20 system), Data were recorded with a left-mastoid reference and offline re-referenced to the linked-mastoid average. Signals were amplified with a g.Nautilus wireless system and sampled at 250 Hz. A 0.1–70 Hz bandpass and 50 Hz notch filter were used during recording, with an additional 25 Hz low-pass filter applied offline.	• In the 300–850 ms time window, only lower delta power (1.7–2.2 Hz) rose after semantically mismatched sentences, and this rise was greater when multisensory input was poorer. • Conditions with limited (exvolved) or richer (involved) sensory input both displayed delta synchronization, with exvolved producing the strongest effect, indicating higher internal concentration	• Learning outcomes were not assessed; future studies should examine short- and long-term gains from sensory enrichment • Filtering above 25 Hz removed high-frequency noise but also prevented analysis of high-beta and gamma bands. • The study did not compare L1 and L2 sentence comprehension processes, which remains an area for future investigation.

	Author(s) & Year, Title	Sample Size & Population	Study design/Task Type	EEG Measurements (Electrode Count)	Key Findings	Limitations
					demands.	
17.	Papagiannopoulou and Lagopoulos (2016), Resting state EEG hemispheric power asymmetry in children with dyslexia	21 subjects with dyslexia and 19 normal readers (8 years old)	Cross-sectional, comparative design (repeated-measures design), 3-minute resting-state EEG (EC), WASI-II, Matrix Reasoning, Dyslexia Screening Test,	19 electrode sites: Fp1, Fp2, Fz, F3, F4, F7, F8, Cz, C3, C4, T7, T8, Pz, P3, P4, P7, P8, O1, and O2), Fast Fourier Transform (FFT) analysis was conducted on 180 artifact-free 1-second epochs. Linked mastoids were used as the reference for the recording. Eye movement artifacts were corrected by using the Gratton et al. regression-based method.	• Increased theta power (3–5 Hz) in the dyslexia group, specifically over frontal regions, Broca's area, and the left hemisphere • Children with dyslexia also showed increased slow-wave activity (delta and theta) in Broca's area relative to Wernicke's area, whereas controls showed no such asymmetry. • Decreased alpha2 and beta power in the left hemisphere in the dyslexia group	• Direct comparison with some earlier studies is constrained due to the use of different statistical tests. • While theta activity was significantly higher in children with dyslexia, the exact origins of this abnormality remain unclear. • The sample was small (40 children; 21 with dyslexia, 19 controls), though this is common in neuroimaging studies.
18.	Meng et al. (2022), The development of brain rhythms at rest and its impact on vocabulary acquisition	53 Chinese children (33 boys, 20 girls, mean age=7.34 years)	Longitudinal, correlational study, 5-minute resting state EEG (EO), vocabulary assessments (Peabody Picture Vocabulary Test (PPVT)), phonological and auditory tasks, non-verbal IQ, backward digit span, parental questionnaires	32-channel Ag/AgCl cap (10-20 system), A portable NeuroScan SynAmps EEG system was used for data acquisition, sampling at 1,000 Hz with a band-pass filter set between 0.1 and 100 Hz. The nose tip served as the reference site, with the ground electrode located midway between FP1 and FP2. Confidence intervals: 95%	• Between ages 7 and 11, resting-state delta, theta, and gamma power decline, while alpha and beta power rise. • Reductions in theta power account for unique portions of variance in expressive vocabulary at ages 9 and 11, and an increase in beta power significantly predicts receptive vocabulary at age 11. • Lower theta power is linked to better expressive vocabulary through the influence of	• The sample was relatively homogeneous; a more socioeconomically diverse participant pool would yield richer information. • The absence of receptive vocabulary measures at earlier time points prevents researchers from establishing whether the observed EEG-band relationships hold consistently across development. • Given the correlational design, researchers cannot infer causality from the significant relations found.

	Author(s) & Year, Title	Sample Size & Population	Study design/Task Type	EEG Measurements (Electrode Count)	Key Findings	Limitations
					phonological awareness at both ages 9 and 11.	
19.	Kepinska et al. (2017), Neural oscillatory mechanisms during novel grammar learning underlying language analytical abilities	42 subjects (18–29)	Experimental EEG study, within-subject learning-and-testing design, LLAMA language aptitude test, artificial grammar learning (main EEG task), grammaticality judgment test	BioSemi ActiveTwo system with 32 Ag/AgCl cap-mounted electrodes, Data were sampled at 512 Hz, online filtered at 0.16–100 Hz, and referenced to CMS. Offline, signals were band-pass filtered (0.3–48 Hz) and re-referenced to bilateral mastoids. Confidence intervals: 95%	• Both learner groups improved grammar learning performance, but the high language analytical ability (LAA) group significantly outperformed the moderate group. • Neural analyses showed that learning was driven by whole-brain functional connectivity in the beta band. • Increasing proficiency was linked to stronger local synchronization in the right hemisphere.	• Relatively small sample size • A fixed 8–12 Hz alpha band was applied across the entire sample, rather than tailoring the range to each participant's individual alpha peak. Although the authors verified that all peaks were within this range, they recognize that fixed boundaries may not capture individual differences or frequency shifts due to cognitive load. • They recommend that future studies calculate individual alpha peaks and set personalized boundaries to avoid bias.