Neurobiology of spoken language in bilingualism: implications from a mind, brain, and education science perspective

Cyntia Bailer, Eduardo Schiller

https://doi.org/10.1590/SciELOPreprints.15016

Submitted on: 2026-02-01
Posted on: 2026-03-30 (version 3)
(YYYY-MM-DD)

Version justification: Adaptações solicitadas pela Revista CadLin

Category of Contribution: Literature Review

NEUROBIOLOGY OF SPOKEN LANGUAGE IN BILINGUALISM: IMPLICATIONS FROM A MIND, BRAIN, AND EDUCATION SCIENCE PERSPECTIVE

NEUROBIOLfOGIA DA FALA NO BILINGUISMO: IMPLICAÇÕES DE UMA PERSPECTIVA DA CIÊNCIA DA MENTE, CÉREBRO E EDUCAÇÃO

Cyntia Bailer, Doutora, Universidade Regional de Blumenau, Departamento de Letras, Blumenau/SC, cbailer@furb.br, ORCID: https://orcid.org/0000-0002-9049-8003.

Eduardo Schiller, Mestre em Educação, Doutorando em Educação no Programa de Pós-Graduação em Educação, Universidade Regional de Blumenau, Blumenau/SC, edo.schiller@gmail.com, ORCID: https://orcid.org/0009-0000-7157-9767.

Abstract: Bilingualism provides a unique lens through which to investigate the neurobiology of spoken language, as it involves dynamic interactions between multiple linguistic systems within the same brain. This narrative review maps the current state of knowledge on the neural mechanisms underlying spoken language in bilingual individuals and how these findings intersect with the field of Mind, Brain, and Education Science (MBE), offering a translational lens that connects neuroscience with pedagogical practice and policy. Key themes emerging from the literature include the neural representation and processing of more than one phonological and lexical systems, the role of cognitive control networks in language selection and switching, and the impact of age of acquisition and proficiency on brain organization. Neuroimaging and electrophysiological studies reveal both overlapping and distinct neural substrates for each language, with evidence for adaptive plasticity in auditory, motor, and frontal control regions. Gaps remain regarding longitudinal trajectories of bilingual language development, the interplay between neural efficiency and cognitive effort, and cross-linguistic differences in spoken language processing. By consolidating findings across disciplines, this review highlights how bilingualism informs broader models of language neurobiology and identifies avenues for future research. We also argue that integrating neurobiological evidence with educational frameworks can contribute to more inclusive pedagogical strategies, early interventions, and informed policies that respect linguistic diversity. At the same time, we emphasize the need for critical reflection to avoid reductionist interpretations and to preserve the social, cultural, and affective dimensions of learning. This article highlights the transformative potential of MBE Science in rethinking how spoken language in bilingualism is understood and supported in educational contexts.

Keywords: spoken language; bilingualism; neurobiology of language; neuroplasticity; Mind, Brain, and Education Science.

Resumo: O bilinguismo oferece uma perspectiva única para investigar a neurobiologia da fala, pois envolve interações dinâmicas entre múltiplos sistemas linguísticos no mesmo cérebro. Esta revisão narrativa mapeia o estado atual do conhecimento sobre os mecanismos neurais subjacentes à fala em indivíduos bilíngues e como essas descobertas se interconectam com o campo da ciência da Mente, Cérebro e Educação (MCE), oferecendo uma perspectiva translacional que conecta a neurociência à prática e às políticas pedagógicas. Os principais temas que emergem da literatura incluem a representação e o processamento neural de mais de um sistema fonológico e lexical, o papel das redes de controle cognitivo na seleção e alternância de idiomas e o impacto da idade de aquisição e da proficiência na organização cerebral. Estudos de neuroimagem e de eletrofisiologia revelam substratos neurais sobrepostos e distintos para cada idioma, com evidências de plasticidade adaptativa em regiões auditivas, motoras e de controle frontal. Ainda existem lacunas em relação às trajetórias longitudinais do desenvolvimento da linguagem em bilíngues, à interação entre eficiência neural e esforço cognitivo e às diferenças entre línguas no processamento da linguagem falada. Ao consolidar descobertas de diversas disciplinas, esta revisão destaca como o bilinguismo contribui para modelos mais amplos de neurobiologia da linguagem e identifica caminhos para pesquisas futuras. Argumentamos também que a integração de evidências neurobiológicas com referenciais educacionais pode contribuir para estratégias pedagógicas mais inclusivas, intervenções precoces e políticas informadas que respeitem a diversidade linguística. Ao mesmo tempo, enfatizamos a necessidade de reflexão crítica para evitar interpretações reducionistas e preservar as dimensões sociais, culturais e afetivas da aprendizagem. Este artigo destaca o potencial transformador da MCE para repensar como a fala no bilinguismo é compreendida e apoiada em contextos educacionais.

Palavras-chave: fala; bilinguismo; neurobiologia da linguagem; neuroplasticidade; ciência da Mente, Cérebro e Educação.

RESUMO PARA NÃO-ESPECIALISTAS: O bilinguismo oferece uma oportunidade única para compreender como o cérebro humano processa a fala, pois envolve o uso de mais de uma língua no mesmo cérebro. Este artigo apresenta uma revisão de trabalhos publicados sobre como bilíngues produzem a fala, articulando essas descobertas com a ciência da Mente, Cérebro e Educação (MCE), com o objetivo de aproximar o estudo do cérebro humano à prática educacional. Os estudos mostram como o cérebro armazena e processa informações em mais de uma língua, o papel do controle cognitivo na escolha do idioma adequado em cada situação, bem como a influência da idade de aquisição e do nível de proficiência na organização cerebral. Apesar dos avanços, permanecem lacunas sobre o desenvolvimento da fala bilíngue ao longo do tempo e sobre a relação entre esforço cognitivo e eficiência neural. Ao integrar evidências de diferentes áreas, este artigo contribui para uma compreensão mais ampla do bilinguismo e argumenta que a integração entre evidências científicas de diversos campos pode apoiar práticas pedagógicas mais inclusivas, políticas educacionais informadas e o respeito à diversidade linguística, sem perder de vista suas dimensões sociais, culturais e afetivas.

INTRODUCTION

Bilingualism, multilingualism, and plurilingualism have become defining features of contemporary societies, driven by globalization, migration, and increased linguistic contact (De Groot, 2011; Grosjean; Li, 2013). Educational systems worldwide increasingly serve learners who use two or more languages in their daily lives, making spoken language a central medium for learning, participation, and social interaction. Despite this reality, much of what is known about the neurobiology of language has been derived from studies of monolingual speakers (Bailer, 2016), often treated implicitly as the developmental norm.

Bilingualism offers a unique window into the neurobiology of spoken language because it involves the coexistence and dynamic interaction of multiple linguistic systems within a single brain. Spoken language in bilinguals is shaped by a range of factors, including age of acquisition (AoA), proficiency, frequency of use, and communicative context, resulting in substantial variability across individuals and settings (Grosjean; Li, 2013). This variability challenges the applicability of monolingual-based models of language development and assessment to bilingual, multilingual, and plurilingual learners, particularly in educational contexts.

While research on bilingualism has expanded considerably, a substantial portion of the literature has focused on literacy, metalinguistic awareness, or language comprehension (Bialystok, 2001; Van Assche; Duyck; Brysbaert, 2013). Comparatively less attention has been given to spoken language, especially from a neurobiological perspective that encompasses speech production, auditory processing, and sensorimotor integration. This gap is especially relevant for classrooms, where spoken language underpins instruction, peer interaction, and the construction of knowledge.

Recent advances in neuroimaging and electrophysiological methods have begun to elucidate how bilingual experience shapes the neural systems supporting spoken language. These findings suggest that bilingualism is associated with experience-dependent neural adaptation rather than deficit. Such deficit might refer to the association of bilingualism with language delay in the L1 with children or the deficit model of L2 learners' language production. However, the body of work remains conceptually fragmented, spanning neuroscience, linguistics, psychology, and education, often without a shared lens to connect biological findings to learning contexts.

In this scenario, a Mind, Brain, and Education (MBE) science perspective (Tokuhama-Espinosa, 2008) offers a transdisciplinary point of convergence for interpreting evidence on spoken bilingualism in ways that are meaningful for educational practice, psychological assessment, and neuroscientific inquiry, without reducing language development to neural mechanisms alone. MBE may offer a translational lens through which the limited number of publications on the neurobiology of spoken language in bilingualism might be understood in relation to development, learning, and lived experience (Ramacciotti, 2024; Guerra, 2011; Tokuhama-Espinosa, 2008; Fischer et al., 2007; Goswami, 2006; Hall, 2005; Schall, 2004).

Against this backdrop, the present narrative review maps recent research on the neurobiology of spoken language in bilingual individuals and examines how these findings can inform a transdisciplinary MBE perspective. Specifically, the review aims to: (i) synthesize neurobiological evidence on spoken language production and processing in bilinguals; (ii) identify key factors shaping neural organization for spoken language, including age of acquisition, proficiency, auditory processing, and social use; and (iii) discuss implications of these findings for teachers, psychologists, and neuroscientists concerned with spoken language development in linguistically diverse classroom contexts.

2 THEORETICAL BACKGROUND

Language acquisition, from a Chomskyan perspective, is seen as an innate biological process rather than a behavior learned through imitation or reinforcement (Fromkin; Rodman; Hyams, 2011). According to researchers as Mampe et al. (2009), the ability to process sounds and extract patterns from them begins in the womb, and, as long as there are adequate stimuli, in typical development, language acquisition will occur naturally. Typically developing infants up to about six months of age display an outstanding sound processing capacity, as they can process any sound of any language (Kuhl; Tsao; Liu, 2003). They begin to specialize processing the sounds that surround them. Such capacity allows infants to discriminate the phonemes of the languages that will be part of their repertoire. By becoming able to discriminate phonemes, infants experiment, recombine, and produce the sounds that will form morphemes, words, and short phrases. They start playing the great game of combination and interaction that is language (Christiansen; Chater, 2023).

Speech involves the production of speech sounds. Milestones in development include babbling at around six months of age, being able to produce the first words at around 12 months and putting words together at around 24 months (Fromkin; Rodman; Hyams, 2011; Visser-Bochane et al., 2020). Various elements of phonology, morphology, semantics, and pragmatics develop in the following years. Children develop language with great variability in the onset time and rate, making it, thus, difficult to describe average language development standards that hold for all children in all languages (Visser-Bochane et al., 2020). In addition, babies who are exposed to more than one language from birth may display an apparent 'delay' when compared to their monolingual counterparts. Such a delay may occur because these babies have to understand two repertoires of sounds that are sometimes distinct and understand when and how to use them – which demands time for processing and storage (Hoff; Core, 2013). Bi/Multi/Plurilingual babies need more time for processing and discriminating phonemes, morphemes and words in all the languages they are exposed to; what means that there is no delay, just a redistribution of temporal resources to accomplish the feat. The repertoire of bi/multi/plurilingual babies, adding their production in all languages, is no smaller than the repertoire of monolingual babies (Fromkin; Rodman; Hyams, 2011). Additionally, children may understand a language they do not yet speak (Foushee; Srinivasan, 2024).

In case of sequential bilingualism, when the additional language(s) is learned after the first, neuroplasticity ensures humans ability to always learn - any language, at any stage of life (Bialystok, 2017). There seems to be a consensus that there is a critical period for learning a first language and sensitive periods for different aspects of additional languages, especially with regards to phonological and prosodic aspects (Fromkin; Rodman; Hyams, 2011). Neuroimaging studies have revealed that "[…] learning a new language can change brain function and anatomy, leaving an enduring mark on the language and cognitive function of children's brains and their cognitive development relative to monolinguals [...]" (Nickerson; Kovelman, 2023, p. 159).

As stated by Grosjean and Li (2013, p. 12), "Bilinguals acquire and use their languages for different purposes, in different domains of life, with different people. Different aspects of life often require different languages". Bilinguals navigate along a continuum of monolingual and bilingual mode; such movement may take place quickly at any time and place. This way, language production in bilinguals is a dynamic process that operates in different language activation states, which impacts the internal processes that precede output as well as the amount of code-switching and borrowing that may take place. In this context, spoken production in bilinguals involves an experience-dependent neurobiological system shaped by timing, social use, and communicative need (Tokuhama-Espinosa, 2001; 2003). And proficiency development is contextual and goal-dependent, not uniform. It is paramount to highlight that the majority of studies focus on adult bilingual language comprehension and production, rather than on bilingual infant and/or child spoken language production.

In this realm, researchers have shown that early acquired languages seem to be integrated into primary language networks (i.e., more left-lateralized), while later-acquired spoken languages recruit a more distributed and bilateral neural network of areas (Bailer, 2016; Hayakawa; Marian, 2019). Multiple spoken languages do not compete for neural space; instead, they are distributed across overlapping networks. Spoken bilingual proficiency is tightly coupled to patterns of social use, with neural maintenance of speech systems reflecting frequency, communicative necessity, and interactional context rather than formal proficiency alone. And neural maintenance of spoken language depends on frequency, domain, and communicative need, not mere exposure.

Although numerous models of speech production have been proposed from different perspectives, there is broad agreement that spoken language production involves at least three core components: conceptualization, formulation, and articulation (Levelt, 2001; Harley, 2008; Grosjean; Li, 2013). During conceptualization, speakers organize a preverbal message while taking into account communicative goals and listener characteristics. In formulation, lexical items are selected and syntactically organized, and articulation executes the motor plan through the articulatory apparatus. Importantly, these processes are highly overlapping in time, as speakers plan and produce speech simultaneously in real communicative contexts.

Within bilingualism, several influential models have attempted to account for language production, including Levelt's model adapted for bilingual speakers (De Bot, 1992), the Inhibitory Control Model (Green, 1998), and the Language-Specific Selection Model (Costa; Miozzo; Caramazza, 1999). While these frameworks have significantly advanced understanding of bilingual language control, they do not fully capture the complexity of spoken language development and production in bilinguals. As noted by Kehoe (2024), no existing model has been developed specifically to account for the phonetic and phonological development of young bilinguals, and, more broadly, a comprehensive model of bilingual speech production remains lacking (Grosjean; Li, 2013).

These theoretical limitations reflect a broader challenge in the study of spoken bilingualism: the difficulty of integrating biological constraints, cognitive mechanisms, developmental trajectories, and social experience within a single explanatory framework. Spoken language development is simultaneously shaped by neural maturation and plasticity, perceptual and motor processes, cognitive regulation, and patterns of social use. As a result, approaches confined to a single level of analysis risk offering incomplete or reductionist accounts.

It is within this context that MBE Science provides a valuable integrative framework. By explicitly connecting findings from neuroscience, cognitive science, and educational research (Ramacciotti, 2024; Guerra, 2011; Tokuhama-Espinosa, 2008; Fischer et al., 2007; Goswami, 2006; Hall, 2005; Schall, 2004), MBE offers a translational lens through which the neurobiology of spoken language in bilingualism can be understood in relation to development, learning, and lived experience. Rather than privileging one level of explanation, an MBE perspective emphasizes the dynamic interaction between brain, mind, and environment, making it particularly well suited to address the complexity and variability inherent in spoken bilingual language development.

3 METHOD

This study is a narrative review of literature examining the neurobiological bases of spoken language in bilingualism. The review was designed to integrate evidence from neuroscience, cognitive science, and language development, with an explicit focus on spoken language production and processing, excluding literacy-based or non-spoken modalities. The methodological approach prioritized conceptual clarity, transparency of selection criteria, and in-depth qualitative synthesis over exhaustive quantitative aggregation.

3.1 Search strategy

A systematic literature search was conducted using Google Scholar, selected for its broad coverage of peer-reviewed articles, dissertations, books, and preprints across neuroscience, linguistics, and cognitive science. The initial search string was: “Neurobiology” “spoken language” “bilingualism”. No temporal restrictions were applied at first. This search returned

2,110 results, which was deemed unfeasible for full screening. To ensure feasibility while maintaining relevance and methodological currency, the search was subsequently restricted to publications from 2022 to 2026, resulting in 756 records.

During preliminary screening, it became evident that a substantial portion of the literature operationalised bilingualism as involving sign languages and/or deaf populations. While such populations are fully bilingual and linguistically valid, they were considered outside the scope of the present review, which focuses exclusively on spoken language neurobiology. To operationalise this delimitation at the search level, exclusion terms were added. The final search string was, therefore, “Neurobiology” “spoken language” “bilingualism” -“deaf” -“sign”. This refined search yielded 326 records. The search was conducted on January 26th, 2026.

3.2 Eligibility criteria

Eligibility criteria were developed iteratively during screening and allowed to overlap, reflecting the multifaceted nature of the literature.

Considering inclusion criteria, studies were included if they: i) addressed bilingual or multilingual individuals; ii) focused on spoken language (production and/or processing); iii) included neurobiological, neurocognitive, or neurophysiological evidence, such as neuroimaging, electrophysiology, or brain-behavior modelling; iv) were empirical studies, dissertations, or theoretically grounded scholarly works; v) were published in English, Portuguese, or Spanish.

As for exclusions, studies were excluded if they met one or more of the following criteria: i) modality mismatch: a) focused exclusively on reading, writing, literacy, or listening without spoken output; b) investigated sign languages, interpreting, translation, or artificial languages; ii) population mismatch: a) involved non-bilingual populations; b) focused primarily on clinical or neurological conditions (e.g., aphasia, autism, ADHD, schizophrenia, Down syndrome, neurorehabilitation) where bilingualism was not the central variable; iii) topic mismatch: a) addressed non-linguistic domains (e.g., mathematics, music, health literacy); b) examined language only tangentially or without neurobiological relevance; iv) linguistic scope mismatch: focused narrowly on specific grammatical forms, accent variation, or dialects without broader implications for spoken language neurobiology; v) methodological or scholarly limitations: a) not available in full text; b) not a scientific or academic text (e.g., book reviews, opinion pieces without analytical grounding); c) duplicate records; vi) language accessibility: published in languages not accessible to the authors of this paper.

3.3 Screening and selection process

All 326 records retrieved through the final search were screened manually. Titles and abstracts were reviewed first, followed by full-text screening where relevance could not be determined at the abstract level. Screening included journal articles, dissertations, theses, and scholarly book chapters. After full-text assessment and application of the eligibility criteria, seven works (as presented on Table 1) met all inclusion criteria and were retained for qualitative synthesis.

Table 1

Selected studies for the final corpus

Extraction Code[1]	Author(s)	Year	Publication type	Title of the study
1	Liu et al.	2025	Journal article	The effect of bilingualism on the functional neuroplasticity of the cerebellum
3	Hämäläinen	2022	PhD dissertation	Neuroanatomy of Bilingualism – Experience-dependent brain changes related to early and late bilingualism
5	Burri	2025	Journal article	Using a Transdisciplinary Lens to Make Sense of My Own Acquisition and Retrieval of Spoken English
7	Spinu et al.	2025	Journal article	An integrative approach to bilingual cognition: preliminary insights into phonetic learning and sensorimotor adaptation
33	Saito et al.	2022	Journal article	Does domain-general auditory processing uniquely explain the outcomes of second language speech acquisition, even once cognitive and demographic variables are accounted for?
68	Wolna	2023	PhD dissertation	Understanding engagement of language control in bilingual speech production
114	Pérez-Navarro et al.	2024	Journal article	Early language experience modulates the cortical tracking of speech

Notes. Data collected by the authors.

[1]Refers to the code in the study package file (Bailer; Schiller, 2026)

3.4 Final corpus

The final corpus consisted of seven studies, including peer-reviewed journal articles, doctoral dissertations, and empirically grounded theoretical contributions. These studies collectively addressed: i) neuroplasticity related to bilingual spoken language use; ii) structural and functional brain differences associated with AoA and proficiency; iii) neural mechanisms of speech production and control; iv) sensorimotor and auditory contributions to spoken bilingualism; v) experience-dependent modulation of spoken language processing. The characteristics of the included studies (authors, year, publication type, methodological approach, and spoken-language focus) are summarized in Table 2.

Table 2

Characteristics of the studies included in the final corpus (n = 7)

	Study	Population	Spoken-language focus	Neurobiological method(s)	Notes
1	Burri (2025)	Early bilingual adult	Acquisition, attrition, and retrieval of spoken English	Transdisciplinary analysis	Narrative + neuroscience
2	Liu et al. (2025)	Monolingual and bilingual adults	Spoken language use, proficiency, and control	Resting-state fMRI	Cerebellar connectivity
3	Spinu et al. (2025)	Early bilingual and monolingual adults	Speech production and phonetic learning	Real-time MRI (rtMRI)	Articulatory focus
4	Pérez-Navarro et al. (2024)	Bilingual children	Cortical tracking of spoken speech	EEG	Acoustic-temporal and lexico-semantic tracking
5	Wolna (2023)	Late bilingual adults	Speech production and language control	Precision fMRI	Language control networks
6	Hämäläinen (2022)	Early and late bilingual adults	Speech production and phonology	Structural MRI, diffusion MRI, TMS	Picture-naming tasks
7	Saito et al. (2022)	Adult L2 learners	Spoken speech acquisition	Behavioral + auditory measures	Auditory processing

Notes. Data collected by the authors.

Given the heterogeneity of methodologies and outcome measures, a qualitative synthesis approach was adopted. Findings were synthesized thematically, with attention to converging and diverging evidence across studies, and interpreted within a framework integrating neurobiological, cognitive, and social dimensions of spoken language development.

4 RESULTS

A central theme across the corpus is that bilingual spoken language is associated with experience-dependent neuroplastic changes, rather than fixed or language-specific neural representations. Evidence from both structural and functional neuroimaging indicates that bilingual experience reshapes neural networks involved in speech processing across the lifespan. Hämäläinen (2022) demonstrated that both early and late bilingualism are associated with measurable structural brain changes, particularly in regions supporting phonological processing and speech production. Early bilinguals showed adaptations within core language-related regions, whereas late bilinguals exhibited experience-related changes in networks linked to higher-level processing and control, highlighting the role of learning history in shaping neural architecture for spoken language.

Complementing these findings, Liu et al. (2025) showed that bilingualism modulates functional neuroplasticity of the cerebellum, a structure increasingly recognized for its role in speech timing, articulation, and language control. Importantly, cerebellar connectivity patterns varied as a function of AoA, proficiency, immersion context, and social language use, underscoring that bilingual neuroplasticity reflects adaptive reorganization rather than simple neural expansion. Together, these studies support a view of spoken bilingualism as a dynamic neurobiological system, continuously shaped by linguistic experience and usage patterns.

Across the reviewed studies, AoA emerged as a critical factor influencing the neural organization of spoken language. Differences between early and late bilinguals were evident in both brain structure and functional engagement during speech-related tasks. Hämäläinen (2022) provided evidence that early bilingual exposure is associated with adaptations in phonological and articulatory networks, consistent with heightened neural sensitivity during early developmental windows. In contrast, late bilingualism was associated with changes in regions implicated in language control and monitoring, suggesting greater reliance on compensatory mechanisms during spoken language processing.

Liu et al. (2025) further demonstrated that AoA modulates cerebello-cortical connectivity, with later-acquired languages engaging neural networks associated with control and coordination to a greater extent. These findings align with models proposing that early acquired spoken languages are more fully integrated into core language networks, whereas later-acquired languages recruit more distributed systems.

Several studies directly addressed the neural mechanisms underlying bilingual speech production, highlighting the role of control networks in managing multiple active languages. Wolna (2023) examined bilingual speech production using precision fMRI and picture-naming tasks, demonstrating that language control mechanisms are engaged even in the absence of overt language switching. Increased activation in frontal control regions was associated with both second-language production and subsequent effects on first-language speech, supporting the view that bilingual speech production inherently involves regulatory processes beyond those required for monolingual speech.

Spinu et al. (2025) extended this perspective by focusing on sensorimotor aspects of speech production. Using real-time MRI, they showed that bilingual speakers exhibit enhanced phonetic learning and articulatory adaptation, particularly with increased proficiency. These findings emphasize that spoken bilingualism involves tight coupling between auditory perception, motor planning, and execution, reflecting an embodied view of speech production.

Together, these studies indicate that bilingual speech production is supported by integrated language-specific, sensorimotor, and control-related neural systems, enabling flexible spoken output across contexts.

Another prominent theme concerns the role of auditory processing as a foundational component of spoken language acquisition in bilinguals. Evidence suggests that individual differences in auditory sensitivity significantly constrain spoken language outcomes. Saito et al. (2022) demonstrated that domain-general auditory processing abilities uniquely predict second-language speech acquisition outcomes, even after accounting for cognitive and demographic variables. These findings indicate that accurate encoding of acoustic information provides a crucial substrate for developing spoken language proficiency, highlighting the importance of perceptual factors in bilingual speech learning.

In developmental populations, Pérez-Navarro et al. (2024) showed that accumulated language experience modulates cortical tracking of speech in bilingual children. Specifically, children exhibited stronger acoustic-temporal tracking in their less-experienced language and stronger lexico-semantic tracking in their more-experienced language. These results reveal that neural processing of spoken speech is finely tuned to experience and proficiency, even in early childhood. It is interesting to note that from the seven works included in the final corpus for analysis, Pérez-Navarro et al. (2024) is the only study that was conducted with bilingual children, demonstrating that this population is understudied.

Beyond neural and cognitive mechanisms, several studies emphasized the socially embedded nature of spoken bilingualism. Patterns of language use across contexts were shown to influence both neural organization and speech processing efficiency. Liu et al. (2025) reported that social language use modulates cerebellar functional connectivity differently from home language use, suggesting that communicative context plays a meaningful role in shaping speech-related neural networks. Similarly, Burri (2025), through a transdisciplinary narrative approach, illustrated how emotionally rich, immersive environments can facilitate the retrieval and reactivation of spoken language, even after periods of reduced use or attrition.

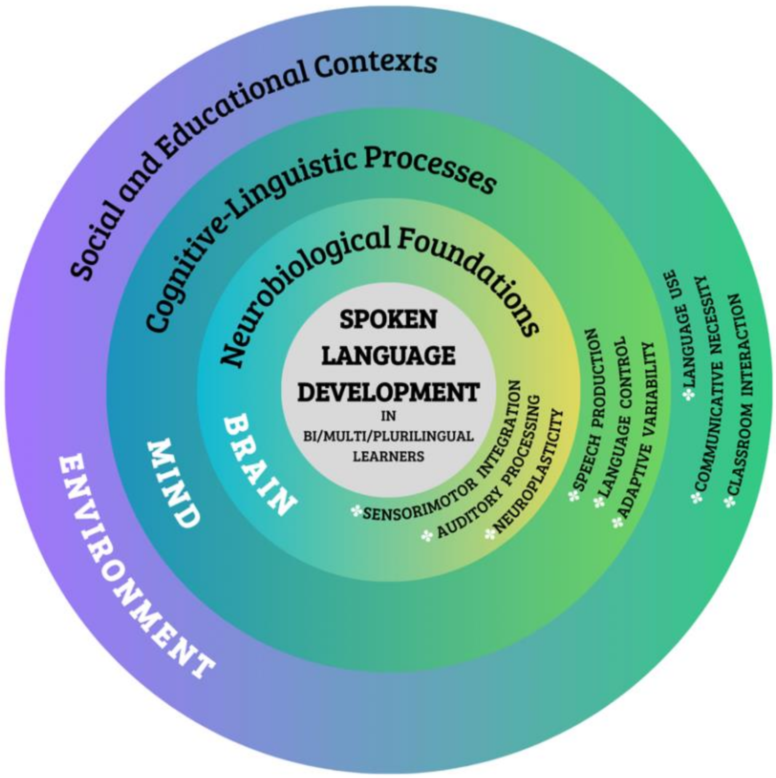
These findings reinforce the view that spoken bilingualism is not solely determined by formal proficiency or exposure, but by meaningful social interaction, affective engagement, and communicative necessity.

5 DISCUSSION

The present narrative review synthesizes recent evidence on the neurobiology of spoken language in bilingualism, revealing a convergent picture of bilingual speech as a dynamic, experience-dependent, and socially embedded neurobiological system. Across neuroimaging, electrophysiological, behavioral, and transdisciplinary approaches, the seven studies included in this review (Burri, 2025; Hämäläinen, 2022; Liu et al., 2025; Pérez-Navarro et al., 2024; Spinu et al., 2025; Wolna, 2023; Saito et al., 2022) collectively demonstrate that spoken bilingualism emerges from interactions among neural plasticity, cognitive regulation, auditory processing, and social language use. Interpreting these findings through a Mind, Brain, and Education (MBE) Science perspective allows neurobiological evidence to inform educational practice while preserving the cognitive, social, and affective dimensions of learning. These interactions are synthesized in Figure 1, which illustrates a transdisciplinary Mind, Brain, and Education framework for spoken language development in bi/multi/plurilingual learners.

Figure 1

Transdisciplinary Mind, Brain, and Education (MBE) framework for spoken language development in bi/multi/plurilingual learners, illustrating how neurobiological, cognitive–linguistic, and social–educational factors interact dynamically to shape spoken language development



Notes. Elaborated by the authors based on the results of this narrative review.
ALT text: Concentric circular diagram with three layers: (1) neurobiological foundations; (2) cognitive-linguistic processes; (3) social and educational contexts.

The results of this review provide empirical grounding for core assumptions outlined in the theoretical background. Early sensitivity to speech sounds and experience-dependent phonological specialization (Mampe et al., 2009; Tokuhama-Espinosa, 2001) are reflected in the neural adaptations observed in both early and late bilinguals (Hämäläinen, 2022; Liu et al., 2025). These findings align with Chomskyan views of language as biologically grounded (Fromkin; Rodman; Hyams, 2011), while simultaneously supporting usage-based accounts that emphasize learning through interaction, variability, and adaptation (Christiansen; Chater, 2023).

Crucially, the reviewed studies reinforce the idea that variability in spoken bilingual development is normative, not a delay or a deficit. Neuroplastic changes associated with age of acquisition, proficiency, and use patterns corroborate arguments by Bialystok (2017) and Tokuhama-Espinosa (2001; 2003) that apparent delays in bilingual children reflect redistribution of cognitive and neural resources rather than deficit. For educators, this challenges monolingual norms often used implicitly in classroom assessment of spoken language.

Neurobiological evidence from Wolna (2023) and Liu et al. (2025) shows that bilingual speech production consistently engages language control networks, even in the absence of overt language switching. These findings provide empirical support for bilingual production models such as the Inhibitory Control Model (Green, 1998) and Levelt-based adaptations (de Bot, 1992; Costa; Miozzo; Caramazza, 1999), while also highlighting their limitations in fully accounting for sensorimotor and developmental dimensions (Kehoe, 2024).

From the seven studies examined in the review process, only one involves children. This does not prevent teachers from seeing direct classroom implications, through an MBE perspective. Increased cognitive effort, hesitations, or cross-language influence during spoken production should not be interpreted as inefficiency or lack of competence. Instead, they reflect adaptive regulation of co-activated linguistic systems, a hallmark of bilingual spoken language. Teachers, coordinators, school psychologists (and other professionals that also take part in the learning process) should therefore interpret variability in spoken output as a normal feature of bilingual development, particularly in contexts where languages serve different communicative purposes (Grosjean; Li, 2013).

From a policy and teacher-education standpoint, classroom-based MBE-informed practices provide concrete models for supporting spoken language development in linguistically diverse contexts. Qualitative evidence from public-school settings in Brazil shows that pedagogical approaches valuing linguistic identity and emotional engagement can strengthen learners' oral confidence and participation (Schiller; Bailer, 2025), reinforcing the need for policies that promote neuroscience-informed, socially grounded language education.

Translating neuroscientific knowledge into educational practice depends critically on teacher education. Experience-based evidence suggests that engaging educators with neuroscientific principles fosters critical reflexivity, autonomy, and more intentional pedagogical decision-making (Bihringer et al., 2024). In this sense, preparing teachers to interpret variability in spoken language development becomes central to supporting bilingual, multilingual, and plurilingual learners in linguistically diverse classrooms.

Findings from Saito et al. (2022) and Pérez-Navarro et al. (2024) highlight the foundational role of auditory processing in spoken bilingual development. Individual differences in acoustic sensitivity and cortical tracking of speech significantly shape spoken language outcomes, independently of general cognitive ability. These results resonate with early developmental accounts emphasizing infants' initial capacity to process all speech sounds before specialization (Tokuhama-Espinosa, 2001).

For classroom practice in contexts where education is delivered through a dominant language that differs from that used in the home environment of the bilingual children, such results underscore the importance of rich, meaningful spoken input, opportunities for attentive listening, and repeated exposure to varied speech patterns. From an MBE standpoint, spoken language instruction should privilege perceptual attunement and oral interaction over premature emphasis on formal accuracy, especially in multilingual classrooms.

Consistent with Grosjean and Li's (2013) holistic view of bilingualism, the reviewed studies demonstrate that neural organization for spoken language is strongly modulated by patterns of social use, communicative necessity, and emotional salience (Liu et al., 2025; Burri, 2025). Spoken bilingual proficiency is therefore context-dependent and goal-oriented, rather than uniform across domains.

This finding has important transdisciplinary implications for MBE. Spoken language development cannot be supported through isolated instructional strategies alone; it requires learning environments that value authentic communication, identity, and affective engagement. For educators, this means creating classroom spaces where multiple languages can be used meaningfully. For psychologists and neuroscientists, it highlights the need to study spoken language development in ecologically valid, socially grounded contexts (Nickerson; Kovelman, 2023).

Taken together, the findings reviewed here support a transdisciplinary MBE framework in which spoken bilingual language development is understood as the product of continuous interaction between brain plasticity, cognitive regulation, perceptual systems, and lived social experience. Rather than offering prescriptive 'brain-based' solutions, MBE provides translational lens that helps align neurobiological evidence with educational practice while avoiding reductionist interpretations.

By linking foundational theories of language acquisition with contemporary neurobiological findings, this review contributes to a more nuanced understanding of what matters for spoken language development in bilingual, multilingual, and plurilingual learners; particularly in classroom contexts where diversity, variability, and social meaning are the norm rather than the exception.

6 CONCLUSIONS

This narrative review examined recent evidence on the neurobiology of spoken language in bilingualism through a Mind, Brain, and Education (MBE) science lens. By synthesizing findings from seven recent empirically grounded studies, the review highlights that spoken bilingual language is not supported by isolated or duplicated neural systems, but rather by experience-dependent, distributed networks that integrate auditory, motor, cognitive control, and social-affective processes. Spoken bilingualism, thus, emerges as a dynamic neurobiological phenomenon, shaped by AoA, proficiency, auditory sensitivity, and (critically) by patterns of meaningful language use.

Across methodologies and populations, the reviewed literature converges on the idea that bilingual spoken language development reflects adaptive neural reorganization, rather than deficit or overload. Early bilingual exposure facilitates integration of multiple spoken languages into core language networks, while later acquisition engages alternative neural pathways that support functional spoken communication. These findings reinforce the view that variability in bilingual speech (such as differences in fluency, timing, or domain-specific performance) represents normal neurocognitive adaptation rather than atypical development.

From a cognitive perspective, bilingual spoken language production is consistently shown to rely on regulatory and control mechanisms that manage co-activated linguistic systems. Importantly, increased neural engagement during bilingual speech should not be interpreted as inefficiency, but as evidence of flexible cognitive regulation supporting communicative goals. At the perceptual level, individual differences in auditory processing emerge as a foundational constraint on spoken language outcomes, underscoring the need to account for perceptual variability in both research and educational contexts.

Crucially, the findings reviewed here demonstrate that spoken bilingualism is inseparable from its social and affective dimensions. Neural maintenance and reactivation of spoken languages depend not only on exposure, but on communicative necessity, emotional salience, and social interaction. This perspective aligns with MBE principles emphasizing that learning occurs at the intersection of brain, mind, and environment, and that educational practices must account for this complexity.

Taken together, the evidence supports a reconceptualization of spoken bilingualism as a neurobiologically grounded yet socially situated system, whose development reflects continuous interaction between neural plasticity, cognitive regulation, and lived experience. Integrating neurobiological insights within an MBE framework allows educators, researchers, and policymakers to move beyond reductionist interpretations and toward more inclusive, responsive approaches to language learning.

We agree with Nickerson and Kovelman (2023, p. 159) when they state that "[…] moving forward, researchers may also consider second language development from a sociocultural perspective, investigating the supportive role of culture on linguistic identity, which may, in turn, be reflected in performance and brain organization for language". Future research should prioritize longitudinal designs that track spoken-language development across changing social and educational contexts, as well as transdisciplinary collaborations that bridge neuroscience, linguistics, and education. Such efforts are essential for translating neurobiological knowledge into pedagogical practices that respect linguistic diversity, support spoken-language development across the lifespan, and promote equitable educational outcomes in increasingly multilingual societies.

Author Contribution Statement

Cyntia Bailer: Conceptualization; Formal analysis; Investigation; Methodology; Visualization; Writing - Original Draft; Writing - Review & Editing.
Eduardo Schiller: Formal analysis; Investigation; Methodology; Visualization; Writing - Original Draft; Writing - Review & Editing.

Competing Interests

The authors declare no competing interests.

Preprint Link

https://preprints.scielo.org/index.php/scielo/preprint/view/15016

https://doi.org/10.1590/SciELOPreprints.15016

Data Availability Statement

Data are available in Zenodo at https://doi.org/10.5281/zenodo.18570668 (CC BY 4.0, The Creative Commons Attribution license allows re-distribution and re-use of a licensed work on the condition that the creator is appropriately credited). The link contains one file (.xlsx) with three tabs: (1) a readme tab; (2) a data tab with seven columns, namely Extraction code, Include/Exclude, Objective reason (criteria), Title, Year, Authors, and DOI/URL; and (3) Extraction_included with six columns, namely Extraction code, Publication type, Population, Spoken-language focus, Neurobiological method(s), and Notes. The search was performed on January 26, 2026 on https://scholar.google.com with the search string: "Neurobiology" "spoken language" "bilingualism" -"deaf" -"sign".

AI Use Statement

The authors declare that no AI tools were used in the creation of this manuscript or in any part of the work reported.

REFERENCES

BAILER, Cyntia. **The neural processing of sentences in bilinguals and monolinguals**: an fMRI study of Portuguese-English bilinguals and Portuguese monolinguals reading comprehension effects on brain activation**.** 2016. 341p. Tese (doutorado) - Universidade Federal de Santa Catarina, Centro de Comunicação e Expressão, Programa de Pós-Graduação em Inglês: Estudos Linguísticos e Literários, Florianópolis, 2016. Disponível em: http://tede.ufsc.br/teses/PPGI0049-T.pdf. Acesso em 20 mar. 2026.

BAILER, Cyntia; SCHILLER, Eduardo. **Study package**-NEUROBIOLOGY OF SPOKEN LANGUAGE IN BILINGUALISM-IMPLICATIONS FROM A MIND, BRAIN, AND EDUCATION SCIENCE PERSPECTIVE [Data set]. Zenodo, 10 Feb. 2026. https://doi.org/10.5281/zenodo.18570668

BIALYSTOK, Ellen. **Bilingualism in development:** Language, literacy, and cognition. Cambridge: Cambridge University Press, 2001.

BIALYSTOK, Ellen. The bilingual adaptation: How minds accommodate experience. **Psychological bulletin,** v. 143, n. 3, p. 233-262, 2017. DOI https://doi.org/10.1037/bul0000099. Acesso: em 20 jan 2026.

BIHRINGER, Katiúscia Raika Brandt; SCHILLER, Eduardo; CRISTOFOLINI, Debora; MICHELLI, Cláudia Regina Pinto; BAILER, Cyntia. Neurociência e educação na formação docente: Um relato de experiência no ensino superior. **Revista Transmutare**, v. 9, n. e17643, p. 1-16, 2024. Disponível em: https://periodicos.utfpr.edu.br/rtr/article/view/17643. Acesso em: 22 jan 2026.

BURRI, Michael. Using a Transdisciplinary Lens to Make Sense of My Own Acquisition and Retrieval of Spoken English. **University of Sydney Journal of TESOL,** v. 4, n. 5, p. 5-32, 2025. DOI https://doi.org/10.5281/ZENODO.17588003. Acesso em: 20 jan 2026.

CHRISTIANSEN, Morten H; CHATER, Nick. **O jogo da linguagem**: a improvisação que mudou o mundo. Rio de Janeiro: Zahar, 2023.

COSTA, Alberto; MIOZZO, Michele; CARAMAZZA, Alfonso. Lexical Selection in Bilinguals: Do Words in the Bilingual's Two Lexicons Compete for Selection? **Journal of Memory and Language**, v. 41, n. 3, p. 365–397, 1999. Disponível em: https://doi.org/10.1006/jmla.1999.2651 Acesso em: 20 jan 2026.

DE BOT, Kees. A Bilingual Production Model: Levelt's 'Speaking' Model Adapted. **Applied Linguistics**, v. 13, p. 1-24, 1992. DOI https://doi.org/10.1093/applin/13.1.1. Acesso em: 20 jan. 2026.

DE GROOT, Annette M. B. **Language and Cognition in Bilinguals and Multilinguals**: An introduction. New York: Psychology Press, 2011.

FOUSHEE, Ruthe; Srinivasan, Mahesh. Infants who are rarely spoken to nevertheless understand many words. **Proceedings of the National Academy of Sciences of the United States of America**, v. 121, n. 23, e2311425121, 2024. DOI https://doi.org/10.1073/pnas.2311425121. Acesso em: 23 mar. 2026.

FISCHER, Kurt W.; DANIEL, David B.; IMMORDINO-YANG, Mary Helen; STERN, Elsbeth; BATTRO, Antonio; KOIZUMI, Hideaki. Why Mind, Brain, and Education? Why now? **Mind, Brain, and Education**, v. 1, n. 1, p. 1-2, 2007. DOI https://doi.org/10.1111/j.1751-228X.2007.00006.x. Acesso em: 20 jan. 2026.

FROMKIN, Victoria; RODMAN, Robert; HYAMS, Nina. **An introduction to language**. 9th ed. Canada: Wadsworth Cengage Learning, 2011.

GOSWAMI, Usha. Neuroscience and education: From research to practice. **Nature Reviews Neuroscience**, v. 7, n. 5, p. 406-413, 2006. DOI: https://doi.org/10.1038/nrn1907. Acesso em: 20 jan. 2026.

GREEN, David W. Mental control of the bilingual lexico-semantic system. **Bilingualism: Language and Cognition**, v. 1, n. 2, p. 67–81, 1998. DOI https://doi.org/10.1017/s1366728998000133. Acesso em: 20 jan. 2026.

GROSJEAN, François; LI, Ping. **The psycholinguistics of bilingualism**. Malden, MA, US: Wiley-Blackwell, 2013.

GUERRA, Leonor Bezerra. O diálogo entre a neurociência e a educação: da euforia aos desafios e possibilidades. **Revista Interlocução**, v. 4, n. 4, p. 3-12, 2011.
HAYAKAWA, Sayuri; MARIAN, Viorica. Consequences of multilingualism for neural architecture. **Behavioral and Brain Functions**, v. 15, n. 6, p. 1-24, 2019. DOI https://doi.org/10.1186/s12993-019-0157-z. Acesso em: 22 mar. 2026.

HALL, John. Neuroscience and education. **Education Journal**, v. 84, p. 27-29, 2005.

HÄMÄLÄINEN, Sini. **Neuroanatomy of bilingualism:** experience-dependent brain changes related to early and late bilingualism. 2022. Tese (Doutorado em Cognição, Aprendizagem, Instrução e Comunicação) – Faculdade de Medicina, Universidade de Helsinki, Helsinki, 2022. Disponível em: http://hdl.handle.net/10138/342101. Acesso em 26 jan. 2026.

HARLEY, Trevor. A. **The psychology of language:** From data to theory. 3rd ed. London: Psychology Press, 2008.

HOFF, Erika; CORE, Cynthia. Input and language development in bilingually developing children. **Seminars in speech and language**, v. 34, n. 4, p. 215-226, 2013. DOI: https://doi.org/10.1055/s-0033-1353448. Acesso em: 20 jan. 2026.

KEHOE, Margaret. The Speech Production of Bilingual Children. *In*: AMENGUAL, Mark (Ed.). **The Cambridge Handbook of Bilingual Phonetics and Phonology**. Cambridge: Cambridge University Press, 2024, p. 285-307.

KUHL, Patricia K.; TSAO, Feng-Ming; LIU, Huei-Mei. Foreign-language experience in infancy: Effects of short-term exposure and social interaction on phonetic learning. **Proceedings of the National Academy of Sciences**, v. 100, n. 15, p. 9096-9101, 2003. DOI https://doi.org/10.1073/pnas.1532872100. Acesso em: 25 mar. 2026.

LEVELT, Willem. J. M. Spoken word production: A theory of lexical access. **Proceedings of the National Academy of Sciences**, v. 98, n. 23, p. 13464–13471, 2001. DOI https://doi.org/10.1073/pnas.231459498. Acesso em: 20 jan. 2026.

LIU, Xiaojin; TONG, Xin; YANG, Ying; LIANG, Yuqi; JIANG, Shan; JIANG, Yongqiang; WANG, Naiyi. The effect of bilingualism on the functional neuroplasticity of the cerebellum.

Bilingualism: Language and Cognition, p. 1–17, 2025. DOI https://doi.org/10.1017/s1366728925100734. Acesso em: 26 jan. 2026.

MAMPE, Birgit; FRIEDERICI, Angela D.; CHRISTOPHE, Anne; WERMKE, Kathleen. Newborns' cry melody is shaped by their native language. **Current biology**, v. 19, n. 23, p. 1994-1997, 2009. DOI https://doi.org/10.1016/j.cub.2009.09.064. Acesso em: 26 jan. 2026.

NICKERSON, Nia; KOVELMAN, Ioulia. Brain imaging methods. *In*: BUTLER, Yuko Goto; HUANG, Becky H. **Research methods for understanding child second language development**. New York: Routledge, 2023, p. 144-163.

PÉREZ-NAVARRO, Jose; KLIMOVICH-GRAY, Anastacia; LIZARAZU, Mikel; PIAZZA, Giorgio; MOLINARO, Nicola; LALLIER, Marie. (2024). Early language experience modulates the tradeoff between acoustic-temporal and lexico-semantic cortical tracking of speech. *iScience*, v. 27, n. 110247, p. 1-17, 2024. DOI https://doi.org/10.1016/j.isci.2024.110247. Acesso em: 26 jan. 2026.

RAMACCIOTTI, Mirela Cunha Cardoso et al. Sobre a Ciência da Mente, Cérebro e Educação: Uma Breve Introdução. **Revista Neurociências e Comportamento**, v. 2, p. 33-76, 2024.

SAITO, Kazuya; CUI, Haining; SUZUKIDA, Yui; DARDON, Diego Elisandro; SUZUKI, Yuichi; JEONG, Hyeonjeon; RÉVÉSZ, Andrea; SUGIURA, Motoaki; TIERNEY, Adam. Does domain-general auditory processing uniquely explain the outcomes of second language speech acquisition, even once cognitive and demographic variables are accounted for? **Bilingualism: Language and Cognition**, v. 25, n. 5, p. 856–868, 2022. DOI https://doi.org/10.1017/s1366728922000153. Acesso em: 26 jan. 2026.

SCHALL, Jeffrey D. On building a bridge between brain and behavior. **Annual Review of Psychology**, v. 55, n.1, p. 23-50, 2004.

SCHILLER, Eduardo; BAILER, Cyntia. Retrato linguístico como processo no desenvolvimento da oralidade em ILA em contexto bi/multi/plurilíngue na escola pública. **Signum: Estudos da Linguagem**, v. 28, n. 1, p. 141-158, 2025. DOI https://doi.org/10.5433/2237-4876.2025v28n1p141-158. Acesso em 28 jan. 2026.

SPINU, Laura; RAFAT, Yasaman; SHEREEN, A. Duke: SUTTON, Bradley P.; PERCIVAL, Maida; MYSLYK, Anastasiia; Kim, Jiyoon. An integrative approach to bilingual cognition: preliminary insights into phonetic learning and sensorimotor adaptation. **Frontiers in Human Neuroscience**, v. 19, n. 1549435, p. 1-18, 2025. DOI https://doi.org/10.3389/fnhum.2025.1549435. Acesso em: 26 jan. 2026.

TOKUHAMA-ESPINOSA, Tracey. **Raising Multilingual Children:** Foreign Language Acquisition and Children. Westport: Bergin & Garvey, 2001.

TOKUHAMA-ESPINOSA, Tracey (Ed.). **The Multilingual Mind:** Issues Discussed by, for, and about People Living with Many Languages. Westport: Praeger, 2003.

TOKUHAMA-ESPINOSA, Tracey Noel. **The scientifically substantiated art of teaching:** A study in the development of standards in the new academic field of neuroeducation (mind, brain, and education science). 2008. Tese (Doutorado em Educação) – Capella University, Minneapolis, Minnesota, 2008. Disponível em: https://www.proquest.com/educationresearchindex/docview/250881375?sourcetype=Dissertations%20&%20Theses. Acesso em 28 jan. 2026.

VAN ASSCHE, Eva; DUYCK, Wouter; BRYSBAERT, Marc. Verb Processing by Bilinguals in Sentence Contexts: The Effect of Cognate Status and Verb Tense. **Studies in Second Language Acquisition**, v. 35, p. 237-259, 2013.

VISSER-BOCHANE, Margot I.; REIJNEVELD, Sijmen A.; KRIJNEN, Wim P.; VAN DER SCHANS, Cees P.; LUINGE, Margreet R. Identifying Milestones in Language Development for Young Children Ages 1 to 6 Years. **Academic Pediatrics**, v. 20, n. 3, p. 421-429, 2020. DOI https://doi.org/10.1016/j.acap.2019.07.003. Acesso em 20 jan. 2026.

WOLNA, Agata. **Understanding engagement of language control in bilingual speech production**. 2023. Tese (Doutorado em Cognitive and Social Neurosciences) – Institute of Psychology, Uniwersytet Jagiellonski W Krakowie, Kraków, 2023. Disponível em: https://ruj.uj.edu.pl/bitstream/handle/item/321816/wolna_understanding_engagement_of_language_control_2023.pdf?file_read_token=59345f77-bb41-4c30-a525-f8ec3957b5e2. Acesso em 26 jan. 2026.