

METHODS SHOWCASE ARTICLE

Integrating Neuroscience into CLIL for Early Primary Learners: Stimulating the Corpus Callosum to Support Learning

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RESUMEN (Spanish)

Los recientes avances en neurociencia están ofreciendo nuevas formas de comprender cómo los niños aprenden idiomas y cómo la enseñanza puede ser más inclusiva en los contextos de aprendizaje integrado de contenidos y lenguas extranjeras (AICLE). A medida que la educación bilingüe se expande por Europa, cada vez es más esencial abordar las diversas necesidades de los alumnos neurodivergentes. Las investigaciones sobre el desarrollo del cerebro muestran que la neuroplasticidad, las funciones ejecutivas (FE) y la comunicación interhemisférica, en particular a través del cuerpo calloso (CC), desempeñan un papel fundamental en el desarrollo de la atención, la autorregulación y el lenguaje durante la primera infancia. Cuando estos procesos se desarrollan de forma atípica, como en el trastorno por déficit de atención e hiperactividad (TDAH) y el trastorno del espectro autista (TEA), los niños pueden encontrar dificultades adicionales en la comunicación y la participación. La incorporación de experiencias rítmicas, basadas en el movimiento y multisensoriales en las aulas bilingües puede mejorar la disposición para aprender y promover la participación de todos los alumnos. Basándose en estas ideas, el Programa de Integración Bilateral diseñado en este trabajo ofrece una secuencia de un año de duración de breves ejercicios diarios de calentamiento cruzado que estimulan la coordinación interhemisférica y fortalecen las FE. Arraigado en la neurociencia y alineado con los marcos educativos europeos y españoles, el programa ofrece un modelo práctico e inclusivo para apoyar el aprendizaje, la atención y el bienestar en la educación bilingüe temprana.

PALABRAS CLAVE

Neuroplasticidad;
Funciones ejecutivas (FE);
Comunicación interhemisférica;
Estudiantes neurodivergentes;
Programa de Integración Bilateral.

ABSTRACT (English)

Recent advances in neuroscience are offering new ways to understand how children learn languages and how teaching can become more inclusive within Content and Language Integrated Learning (CLIL) contexts. As bilingual education expands across Europe, addressing the diverse needs of neurodivergent learners has become increasingly essential. Research on brain development shows that neuroplasticity, executive functions (EFs), and interhemispheric communication, particularly through the corpus callosum (CC), play a central role in the growth of attention, self-regulation, and language during early childhood. When these processes develop atypically, as in attention-deficit/hyperactivity disorder (ADHD) and autism spectrum disorder (ASD), children may encounter additional challenges in communication and participation. Embedding rhythmic, movement-based, and multisensory experiences into bilingual classrooms can enhance readiness to learn and promote engagement for all pupils. Building on these insights, the Bilateral Integration Programme designed in this work provides a year-long sequence of short, daily cross-lateral warm-ups that stimulate interhemispheric coordination and strengthen EFs. Rooted in neuroscience and aligned with European and Spanish educational frameworks, the programme offers a practical, inclusive model for supporting learning, attention, and wellbeing in early bilingual education.

KEYWORDS

Neuroplasticity;
Executive functions (EFs);
Interhemispheric communication;
Neurodivergent learners;
Bilateral Integration Programme.

1. Neurobiological Foundation of Second Language Acquisition

Early childhood is a period of rapid brain growth and high neuroplasticity (Ferrè & Aribau, 2008). At this stage, language learning involves sensorimotor, cognitive, and social systems working together across both brain hemispheres. Understanding these neurobiological foundations helps educators design bilingual programmes suited to children's developmental and linguistic needs.

1.1. Brain Plasticity in Early Language Acquisition

Neuroplasticity is the brain's capacity to reorganise itself by forming, modifying, and strengthening neural connections in response to both internal experiences and external stimuli (Gazerani, 2025). In simple terms, it is the brain's ability to change through learning and experience. This capacity is especially pronounced in early childhood, when brain networks are highly sensitive and adaptable.

Studies in neuroscience using non-invasive imaging techniques, such as magnetoencephalography (MEG) and event-related potentials (ERP), have shown that language processing begins in infancy, long before speech emerges (Kuhl, 2010). As Sousa (2017) observed, "the brain of a newborn is not a tabula rasa, as was previously believed" (p. 33). Indeed, infants have the ability to distinguish phonetic contrasts from any language. Over time, this universal sensitivity narrows as the brain adapts to the sounds it hears most frequently, a process known as neural commitment (Kuhl, 2011). Through this experience-dependent plasticity, the brain determines which sounds to strengthen and which to weaken, a phenomenon commonly called in neuroscience "window of opportunity."

However, language learning does not happen in isolated brain "language areas." It involves broad neural networks integrating sensory, motor, and affective systems, whose coordination supports language acquisition (LA) (Friederici, 2011). Because brain plasticity is greatest in early childhood, this integration offers an opportunity to educators to design effective and inclusive educational interventions, particularly for neurodiverse learners. Experiences such as bilingualism can influence this process, promoting structural changes not only in language-specific cortical regions but also in broader networks of cognitive control (Pliatsikas, 2020). The Dynamic Restructuring Model (DRM) helps explain this process. It proposes that managing two or more languages strengthens grey- and white-matter connections and enhances the brain's flexibility and integration (Pliatsikas, 2020).

Around age five, most children can follow complex sentences, recognise familiar sound patterns, and keep their attention for up to fifteen minutes (Miguel, n.d.). This developmental phase coincides with rapid structural changes in the brain. Among these developments, myelination, the process of coating neural fibres with a fatty layer that speeds information transfer between brain regions, supports efficient inter-regional communication. This process facilitates the integration of phonological, semantic, and syntactic processing (Friederici, 2011; Kennedy, 2006). Bilingual experience can reinforce these connections, boosting language control as well as general cognitive flexibility (Costa, 2012).

Environmental input is also a key factor, Kuhl (2011) emphasises that early language mastery "requires learning in a social context" (p. 1). Similarly, Kennedy (2006) notes that meaningful, content-based language environments stimulate multiple sensory channels, increasing the relevance of linguistic input. Furthermore, activities that involve movement and multiple senses can further support learning by harnessing brain plasticity to support language and cognitive development (Shams & Seitz, 2008). Even though brain plasticity is particularly high in early childhood, it is still shaped by both biological maturation and experience (Kuhl, 2010; Kennedy, 2006). Consequently, it is vital to provide all children, especially those from

disadvantaged backgrounds or with neurodevelopmental conditions, with access to stimulating bilingual environments (Kuhl, 2011).

Neuroplasticity supports all learning. However, children with ADHD and ASD exhibit distinct neural pathways that shape both cognition and behaviour. In ASD, atypical brain maturation often results in either excessive or reduced connectivity between brain regions (Uddin et al., 2013). Similarly, children with ADHD show delayed white-matter development, particularly in attention networks and in the coordination between the brain's hemispheres (Shaw et al., 2015). These variations can affect phonological, grammatical, and pragmatic aspects of language acquisition (Uddin et al., 2013).

Yet, the high plasticity of young brains offers strong potential for bilingual learning. This flexibility can be channelled through well-designed programmes. Such initiatives support emotional, cognitive, and physical development.

1.2. Critical and Sensitive Periods of Language Acquisition

Neuroscientific research distinguishes between *critical* and *sensitive* periods of brain development. A critical period is a biologically predetermined window in which learning a specific skill can be acquired most effectively. Beyond this window, learning becomes restricted or, in some cases, impossible (Simply Psychology, 2023). By contrast, a sensitive period denotes a developmental stage optimal for learning, after which acquisition remains possible but less efficient. Contemporary language acquisition theory recognises that language development is affected by a sequence of overlapping sensitive periods, and the degree of plasticity differs among the diverse areas of language (Hensch, 2005; Thomas & Johnson, 2008; Werker & Hensch, 2015).

Early evidence for critical periods came from Konrad Lorenz's studies on filial imprinting (Thomas & Johnson, 2008). Since then, research has shown that some neural systems, particularly those involved in early sensory processing, display critical-period properties. In contrast, higher cognitive functions such as language develop through longer and more flexible sensitive phases (Thomas & Johnson, 2008).

Accordingly, sensitive periods arise as brain circuits adapt to environmental input, progressively refining and specialising. Thus, language-sensitive windows are fluid and overlapping rather than rigidly bounded. This flexibility reflects the brain's dynamic capacity for experience-dependent change (Hensch, 2005; Werker & Hensch, 2015).

In early language learning, sensitive periods appear differently across various areas of language. For instance, in phonological processing, newborns can distinguish all human speech sounds, but between six and twelve months this broad phonetic sensitivity narrows as the brain adapts to the sounds of the surrounding language(s) (Kuhl, 2010; Werker & Hensch, 2015). Kuhl (2010) demonstrated that this experience-driven tuning of neural circuits forms durable phonological categories that influence later literacy. Bilingual infants, however, display greater phonetic flexibility, as dual-language exposure can extend the sensitive period for sound discrimination (Kuhl, 2011; Werker & Hensch, 2015).

Besides phonology, grammatical development follows a distinct trajectory. Newport (1989) demonstrated that children learning a second language (L2) before age seven were far likelier to attain native-like grammatical competence, whereas late learners showed reduced syntactic ability. Similarly, Werker and Hensch (2015) confirmed that sensitivity to morphosyntax declines significantly past age seven, though explicit learning remains possible. By contrast, lexical acquisition continues throughout life, since vocabulary learning relies more on memory and conceptual association than on fixed neural timing (Thomas & Johnson, 2008).

Accordingly, the overlapping and extended nature of sensitive periods thus supports the rationale for early bilingual education. Although certain linguistic abilities are most effectively acquired early in life, the capacity for successful language learning remains open through the early primary years. This is particularly true when children engage in rich, socially interactive, and meaningful communicative contexts that nurture both cognition and emotion.

1.3. Neural Basis of L2 Acquisition

Classical models of neurolinguistics located language almost exclusively in the left hemisphere, particularly in Broca's and Wernicke's areas. Contemporary neuroscience, however, demonstrates that language emerges from distributed and interactive networks across both hemispheres. Friederici (2011) demonstrated, using evidence from functional magnetic resonance imaging (fMRI) and positron emission tomography (PET), that language processing is not confined to discrete cortical areas but arises from dynamic interactions among multiple brain systems.

The inferior frontal gyrus (IFG) and posterior superior temporal gyrus (STG) form an integrated frontotemporal network by interacting via the arcuate and superior longitudinal fasciculi. These findings challenge the notion of a localised "language organ" and support the view of language as a bilateral, networked function.

From birth, infants show distributed brain activity in response to speech, indicating that language processing begins long before the brain's hemispheres become specialised, a process known as lateralisation (Friederici, 2011). Auditory and motor cortices cooperate during speech perception and production, reflecting how closely hearing and speaking are linked (Pulvermüller & Fadiga, 2010). Motor regions are also engaged when processing action-related words. For instance, words such as *grasp* or *kick* activate the corresponding motor areas in the hand or leg, evidencing the embodied nature of semantic representation (Pulvermüller, 2013).

In addition, emotional aspects of speech, such as prosody, activate limbic and paralimbic structures like the amygdala, anterior cingulate cortex, and orbitofrontal areas, which support attention and affective interpretation (Schirmer & Kotz, 2006).

Language learning in early childhood is thus embodied, social, and multimodal. Kuhl (2011) demonstrated that socially engaging experiences foster "neural commitment" to linguistic representations, enhancing learning. This evidence aligns with Pulvermüller's

(2013) embodied cognition theory, in which auditory, motor, and affective systems interact to build meaning.

As these systems mature, the organisation of the language network also changes. By ages five to six, the main language areas of the brain are already in place, although the connections between them are still developing (Friederici, 2011). At this stage, children use both sides of the brain for language, while adults rely more on the left side. The pathway that links regions for grammar and sentence structure continues to mature throughout childhood. In contrast, the network that supports understanding word meanings is already well developed from infancy.

At this stage of development, the brain continues to refine its internal connections through two key processes. Synaptic pruning, which removes weaker or unused connections between neurons, and myelination, which coats active nerve fibres with a fatty layer that speeds communication between regions, strengthen the brain's efficiency (Friederici, 2011). Together, these processes support vocabulary growth and the gradual mastery of grammar.

Children with neurodevelopmental conditions often show different patterns of brain connectivity. In ASD, communication between the two hemispheres may be reduced, affecting rhythm, meaning, and sentence structure (Kana et al., 2014). In ADHD, differences in the brain areas that support attention, planning, and language control can make it harder to manage complex grammar or switch between languages (Vaidya & Stollstorff, 2008). These variations highlight the importance of multisensory and movement-based teaching methods that engage several brain systems and can enhance bilingual learning for all children.

Bilingual experience enhances interhemispheric communication and cognitive flexibility. In this regard, Petitto et al. (2012) used functional near-infrared spectroscopy (fNIRS) to show that bilingual children activate similar neural mechanisms for both languages but demonstrate stronger cross-hemispheric connectivity than monolinguals. Such distributed processing supports attentional control and adaptive learning (Petitto et al., 2012).

These findings support multisensory and emotionally engaging approaches in early L2 teaching. Activities such as movement, songs, and role-play have been shown to enhance word learning in children (Macedonia, 2019). For neurodivergent learners, these approaches also improve attention and interhemispheric coordination. Since five- and six-year-olds are still developing syntactic skills, bilingual instruction should prioritise interactive experiences over formal grammar. Sensitive periods for language in ADHD and ASD may differ. In ASD they often involve delayed phonological or pragmatic growth (Eigsti et al., 2011; Kuhl, 2010), while in ADHD they are characterised by attention-related difficulties (Korrel et al., 2017). Therefore, flexible and inclusive bilingual programmes are essential to meet diverse developmental needs.

2. The Role of the Corpus Callosum in Language Acquisition

Early language acquisition depends on coordinated activity between the brain's hemispheres, mediated by the corpus callosum (CC). In five and six-year-olds, this interhemispheric integration supports the motor, sensory, and cognitive functions fundamental in bilingual learning. Understanding CC functioning can thus inform the design of bilingual programmes that promote whole-brain language processing.

2.1. *Corpus Callosum Development in Early Childhood and Bilingualism*

The CC is the largest white-matter structure in the brain, containing over 300 million myelinated nerve fibres, axons, which interconnect the two hemispheres (Hofer & Frahm, 2006). It acts as a communication bridge, enabling the exchange of information between both sides of the brain and supporting sensory, motor, and cognitive functions. Anatomically, it lies within the medial longitudinal fissure and is divided into the rostrum, genu, body, and splenium, which connect distinct cortical regions from the prefrontal to the occipital lobes (Mathias, 2023).

Most of its fibres link matching areas in the two hemispheres, homotopic connections, while others link different areas, heterotopic connections. Large diameter axons transmit sensorimotor information rapidly, whereas smaller ones connect regions engaged in complex processes such as language and executive control (Aboitiz et al., 1992).

The CC begins forming around the tenth week of gestation and its maturation, particularly the progressive myelination of callosal fibres, continues into adolescence (Bloom & Hynd, 2005). Around ages five to six, interhemispheric communication becomes faster and more efficient, coinciding with advances in phonological development, motor coordination, and hemispheric lateralisation. For example, during this period, children's ability to break words into individual sounds, a skill known as phonemic segmentation, increases from roughly 17% to 70% accuracy (Miguel, n.d.).

At this stage, children show rapid growth in interhemispheric connectivity, linguistic proficiency, and metalinguistic awareness (Friederici, 2011). They begin transferring information across sensory modalities, distinguishing subtle phonetic contrasts, and maintaining longer attention spans. These skills rely on precise interhemispheric communication which is facilitated by the CC. For instance, the regions in the left hemisphere process phonemic detail, while the right regions analyse prosody and timing information (Friederici, 2011; Schirmer & Kotz, 2006). Such bilateral interaction becomes critical as children learn to interpret pragmatic meaning, sarcasm, irony, or indirect requests, which require sensitivity to both literal content and social context (Paul, 2007).

Experience and the environment play a major role in shaping callosal organisation. Enriched linguistic and sensorimotor environments strengthen interhemispheric connectivity, whereas limited stimulation correlates with atypical maturation (Fields, 2008; Mackey et al., 2012). This shows that white-matter development is experience-dependent, adapting to learning and environmental demands (Fields, 2010; Lebel & Deoni, 2018).

One of the most cognitively intensive experiences influencing CC structure is bilingualism. Managing two languages requires constant coordination between lexical, grammatical, and pragmatic systems, which imposes higher interhemispheric demands (Mohades et al., 2012). Brain imaging shows that bilinguals engage broader, more bilateral networks than monolinguals, with the CC mediating processes such as code-switching, cross-linguistic transfer, and metalinguistic control (Luk et al., 2011).

Bilingual learners juggle two phonological systems, grammar rules, and vocabularies while adjusting language use to social context. Therefore, an effective interaction between the two hemispheres is essential. The left hemisphere supports linguistic form, while the right contributes to affective tone and communicative intent. This interplay enhances metalinguistic sensitivity and executive control, the mental skills that help learners shift focus, inhibit interference, and switch between languages (Costa, 2012).

The ages five to six constitute a sensitive window when increased myelination and plasticity facilitate L2 consolidation (Costa, 2012; Miguel, n.d.). During this period, children begin to choose which language to use depending on the situation and their listener. This behaviour relies on connections between the prefrontal cortex and the CC, which support attention shifting and inhibition. In turn, the CC continues reorganising in response to bilingual experience, becoming increasingly specialised through use (Pliatsikas, 2020).

Brain imaging confirms that early bilingual exposure changes both the structure and function of the CC. Coggins et al. (2004) found clear anatomical differences between bilingual and monolingual adults. They concluded that “the corpus callosum undergoes adaptation to accommodate multiple language facility” (p. 72). These adaptations likely involve greater myelination and fibre density, which improve coordination and reduce interference between languages.

Similarly, Negin et al. (2016) observed larger callosal volume in simultaneous bilinguals, especially in the anterior and midbody regions. These areas are crucial for managing interference and supporting executive control. Together, these findings support Mohades et al.’s (2012) conclusion that bilingualism brings about early structural changes in the CC.

Building on this, diffusion-tensor imaging (DTI) studies offer further insight into these adaptations at a finer scale. Mohades et al. (2012) found that simultaneous bilingual children had more complex fibre organisation in the front part of the CC than monolinguals, suggesting richer interhemispheric connections. In contrast, sequential bilinguals, who learn their second language later, showed intermediate patterns. This finding suggests that bilingual experience gradually reshapes the brain.

Comparative analyses further reveal that bilingualism enhances white-matter integrity of the front regions of the CC, associated with attention control, inhibition, and cognitive flexibility (Luk et al., 2011; Pliatsikas, 2020). For example, bilingual children often demonstrate better attention span and an improved ability to switch between tasks, thanks to stronger connectivity in these brain regions. These EFs help bilingual learners alternate between languages and reduce interference (Mohades et al., 2012). Stronger anterior connectivity implies better integration of syntactic, lexical, and phonological information across hemispheres (Van der Knaap & Van der Ham, 2011). In contrast, monolingual children,

who operate a single language system, show less interhemispheric engagement and reduced white-matter specialisation (Pliatsikas, 2020). The cumulative evidence therefore portrays the CC as a dynamic, experience-dependent structure that reorganises in response to bilingual demands.

Beyond white-matter connectivity, research links bilingualism to cortical surface area differences, especially in the praecuneus, indicating long-term structural adaptation to managing two languages (Pliatsikas et al., 2020).

2.2. Corpus Callosum Development in Children with ADHD and ASD

Neurodevelopmental conditions such as ADHD and ASD share atypical patterns of CC development, which can significantly affect language and other cognitive functions (Ferre & Aribau, 2008). The most consistent findings across both profiles include altered growth trajectories, microstructural abnormalities, and disrupted interhemispheric connectivity. These differences can weaken EFs, phonological awareness, pragmatic language, and motor-sensory coordination (Travers et al., 2015; Zhang et al., 2023).

For bilingual learners with ADHD or ASD, these atypical neural patterns pose particular challenges, as successful bilingual acquisition depends on flexible interhemispheric connectivity to manage two linguistic systems across social and communicative contexts (Costa, 2012; Pliatsikas, 2020). Understanding CC development in these groups is therefore essential to guide inclusive bilingual pedagogy.

In the case of ADHD, structural anomalies in the CC are frequently observed, though their exact location varies. Seidman et al. (2005) found consistent reductions in the splenium, the rear section of the CC that connects visual and sensory regions, while changes in the front areas were less consistent. Connaughton et al. (2022) also reported irregularities in both the front and back white-matter fibres. Overall, ADHD involves atypical CC development affecting interhemispheric connections. This affects attention, working memory, and executive control, all key processes in bilingual management.

In ASD, CC alterations are typically marked by reduced volume across the genu, body, and splenium (Travers et al., 2015). Courchesne et al. (2007) linked these differences to early brain overgrowth followed by irregular white-matter development. Brain imaging studies show that younger autistic children may initially display unusually high connectivity between brain regions, suggesting temporary overcommunication. As development progresses, this connectivity often declines, reflecting weaker long-range communication pathways (Travers et al., 2015). These irregularities disrupt the integration of social and linguistic information, making it harder to interpret tone, context, and meaning in conversation (Kana et al., 2014). At the same time, CC development in ASD varies widely among individuals. Nordahl et al. (2015) found sex-related structural differences, while Zhang et al. (2022) reported that callosal volume changes with cognitive ability and other developmental factors. Together, these findings highlight that autism encompasses diverse patterns of brain organisation rather than a single structural profile.

Despite distinct neural profiles, ADHD and ASD share overlapping disruptions in interhemispheric pathways. Posterior callosal anomalies are more typical in ADHD, whereas broader reductions occur in ASD. Children with co-occurring ADHD-ASD profiles often exhibit pronounced language control and EFs deficits (Connaughton et al., 2022; Travers et al., 2015; Uddin et al., 2013).

In ADHD disrupted CC organisation may impair attentional control and language switching, increasing interference from non-target languages (Wu et al., 2025). Similarly, in ASD reduced CC integrity affects grammatical, prosodic, and pragmatic processing (Kana et al., 2014). Both conditions therefore make managing two languages more challenging, particularly in multilingual learning environments.

Motor-sensory integration, fundamental to many bilingual pedagogies involving movement and rhythm, can also be affected. Children with ASD or ADHD frequently present motor-coordination difficulties linked to CC anomalies (Demopoulos et al., 2017; Mostofsky et al., 2009). These may impair articulation, phonological processing, and synchronisation of speech with movement-based learning, elements central to early bilingual education (Travers et al., 2015).

Since the CC remains malleable throughout childhood, bilingual exposure may enhance interhemispheric connectivity and promote adaptive neural reorganisation (Pliatsikas, 2020; Uddin et al., 2013). Longitudinal L2 studies show that interhemispheric coordination evolves with proficiency, with reduced left-hemispheric inhibition and increased right-hemisphere engagement at advanced stages (Wei et al., 2024), demonstrating experience-dependent CC plasticity. Thus, multisensory and movement-based bilingual learning may offer alternative neural pathways that support language development in children with ADHD and ASD (Costa, 2012; Mostofsky et al., 2009; Pliatsikas, 2020).

Integrating cross-lateral movement into bilingual classrooms can improve engagement and cognitive coordination, both vital for L2 learning, especially in neurodivergent children. Because the brain regions for language are most receptive in early childhood—narrowing after about age five and again around ten to twelve—early multisensory exposure is crucial. Johnson and Newport (1991) found that children who learned English between ages three and seven achieved near-native proficiency, while later learners showed lower attainment. Early, movement-based bilingual activities therefore strengthen neural connectivity and language processing during the brain's most plastic stage (Thomas & Johnson, 2008).

3. Neurodevelopmental Disorders and L2 Acquisition

ADHD and ASD, usually diagnosed in early childhood (American Psychiatric Association, 2013), involve cognitive and linguistic differences that influence bilingual learning (Thapar et al., 2017; Geurts & Embrechts, 2008). Inclusive pedagogies are essential to support language and cognitive development (Carballo & Portero, 2018; Miguel, n.d.).

3.1. ADHD and ASD in Early Childhood: Characteristics and Overlapping Traits

ADHD and ASD are neurodevelopmental disorders increasingly identified in early childhood. Specifically, ADHD often persists into adolescence and adulthood and is characterised by persistent patterns of inattention, hyperactivity, and impulsivity that affect academic, social, and emotional functioning (American Psychiatric Association, 2013; Thapar et al., 2013). The *Diagnostic and Statistical Manual of Mental Disorders* (DSM-5) distinguishes three presentations:

- predominantly inattentive (difficulties with focus and organisation),
- predominantly hyperactive-impulsive (restlessness and impulsive behaviour),
- combined, which includes features of both (APA, 2013).

Similarly, ASD involves persistent difficulties in social communication and restricted or repetitive behaviours (APA, 2013). Symptoms emerge early in life and vary in severity, hence its description as a spectrum. Common traits include limited non-verbal communication, insistence on sameness, and unusual sensory responses. Neuroimaging shows atypical connectivity in regions involved in social, language, and sensory integration, including the amygdala, temporal lobes, and cerebellum (Di Martino et al., 2013; Giedd & Rapoport, 2010).

ADHD and ASD, once considered distinct under DSM-IV-TR criteria, are now recognised as potentially co-occurring in the DSM-5 (APA, 2013). Evidence indicates overlapping phenotypes with shared deficits in attention, social interaction, and EF (Craig et al., 2015). Even in early childhood, children may display features of both; autistic learners often show hyperactivity and inattention, while those with ADHD may exhibit social and pragmatic communication difficulties (Thapar et al., 2013).

Moreover, both conditions share difficulties in executive functioning, particularly in cognitive flexibility, working memory, planning, and inhibition, skills essential for learning and language development. Emotional regulation and sensory processing challenges are also common, often leading to impulsivity, behavioural issues, and reduced engagement in social learning (Geurts & Embrechts, 2008; Helland et al., 2010). These challenges typically emerge during early schooling, when structured tasks demand sustained attention and reasoning.

Atypical brain rhythms, particularly in the slower (theta) and faster (gamma) frequency ranges, can disrupt speech timing and sound processing, contributing to language difficulties in ADHD and ASD (Giraud & Poeppel, 2012). Interventions that use rhythm, rhyme, and melody, collectively referred to as *prosodic scaffolding*, can help the brain re-establish more synchronised timing patterns (Goswami & Leong, 2013). These overlapping symptoms likely arise from shared differences in brain networks that manage EF, attention and social understanding (Di Martino et al., 2013; Fair et al., 2012). Furthermore, abnormal interhemispheric communication may contribute to similar behavioural patterns, suggesting a developmental continuum shaped by genetics, maturation, and environment (Thapar et al., 2017; Uddin et al., 2017).

Neuroimaging shows that ADHD involves delayed prefrontal maturation affecting executive control, while ASD features atypical development in regions for social cognition, language,

and motor skills (Giedd & Rapoport, 2010; Lenroot & Giedd, 2006). Both also present white-matter irregularities in the CC, disrupting interhemispheric communication and hindering sensory, linguistic, and motor integration (Frazier & Hardan, 2009). For young bilingual learners, these deficits can complicate language and literacy development. Moreover, overlapping traits often blur diagnostic boundaries. Hyperactivity in autistic children or social withdrawal in ADHD may mask co-occurring features, delaying support and highlighting the need for nuanced, developmentally sensitive assessment (Francés et al., 2022).

Language profiles in ADHD and ASD are highly variable but show distinct patterns. Children with ADHD often struggle with narrative cohesion, expressive language, and pragmatics due to limited attention and working memory, leading to impulsive or disorganised speech (Geurts & Embrechts, 2008). In contrast, children with ASD typically face more persistent challenges, delayed speech onset, echolalia, reduced gesture use, and atypical prosody, despite adequate vocabulary and syntax, reflecting broader deficits in discourse and social-pragmatic communication (Eigsti et al., 2011; Helland et al., 2010; Norbury & Sparks, 2013).

The overlap between ADHD and ASD often complicates classroom practice, as strategies suited to one condition may overlook traits of the other. This comorbidity highlights the importance of early identification and specialised teacher training to recognise differences in attention, language, and motor coordination during peak neuroplasticity (Helland et al., 2010; Portellano & García, 2014; Francés et al., 2022).

Rich language experiences, such as shared reading and responsive dialogue, strengthen the brain networks that support language and EF, which often develop differently in these learners (Romeo et al., 2018; Lukito et al., 2020). Structured interventions like the *Nuffield Early Language Intervention (NELI)* show lasting gains in vocabulary, listening, and literacy, highlighting schools' role as supportive environments for children at developmental risk (Education Endowment Foundation & RAND Europe, 2020; Hulme et al., 2025).

3.2. Implications for Early Bilingual Education

Neurodevelopmental conditions like ADHD and ASD exhibit distinctive developmental trajectories with important implications for early bilingual education. During this period, around ages five and six, rapid advances in language, EF, and interhemispheric integration coincide with the onset of literacy, as children begin linking graphemes and phonemes across one or more languages (Lenroot & Giedd, 2006; Nkurunziza, 2024). In ADHD and ASD, these typical developmental processes interact with atypical neural patterns, influencing attention, sensory integration, and language coordination (Gazzaniga, 2005; Lenroot & Giedd, 2006).

As a consequence, children with ADHD and ASD often show delays or atypical patterns in phonology, syntax, and pragmatics due to EF deficits affecting attention, memory, and flexibility (Helland et al., 2012; Kuhl et al., 2005). ADHD learners struggle with sustained focus, while autistic children face social-pragmatic challenges, especially in dynamic L2 contexts. These difficulties directly shape participation in bilingual education (Craig et al., 2016; Norbury & Sparks, 2013).

Until recently, educational and clinical practice often discouraged bilingual exposure for neurodivergent children, fearing added cognitive strain (Digard et al., 2023; Howard et al., 2019). However, research indicates that bilingualism does not exacerbate language or attention difficulties in ASD or ADHD and can even improve cognitive flexibility and social interaction in autistic learners (Köder et al., 2022; Howard et al., 2021).

The focus has therefore shifted from questioning *whether* neurodivergent children can be bilingual to understanding *how* bilingual education can adapt to their developmental profiles, moving beyond monolingual, deficit-based models toward inclusive, neurodevelopmentally informed practice (Andreou & Skrimpa, 2022).

Neuroanatomically, bilingualism engages attentional control, inhibition, and working memory, areas often underdeveloped in ADHD and ASD (Andreou et al., 2020; Bialystok et al., 2012). Managing two linguistic systems promotes functional connectivity and white-matter plasticity, particularly in the CC (Felton et al., 2017), reinforcing normal interconnectivity and supporting metalinguistic awareness and phonological decoding, key components of early reading (Lenroot & Giedd, 2006; Mohades et al., 2012; Bialystok et al., 2012).

However, these benefits depend on pedagogical environments attuned to individual cognitive profiles. While CLIL is effective for many learners, equires managing several tasks at once and understanding abstract ideas, which can be challenging for those with ADHD or ASD (Segura, 2023; Sorge et al., 2017). Without differentiation, CLIL's contextualised input can impose excessive cognitive load on students (Le Cunff et al., 2024; Madrid & Pérez, 2018). Learners with weak working memory may struggle to process new content and unfamiliar L2 structures simultaneously (Holmes et al., 2014). In turn, ASD pupils may find implicit social-pragmatic cues in large, fast-paced groups especially demanding (Reindal et al., 2023).

The gap between inclusive policy and classroom practice in Spain has been underscored by initiatives such as the ADiBE project. Although national frameworks promote "*atención a la diversidad*," many bilingual programmes still lack flexibility in curriculum, teacher preparation, and assessment for neurodivergent learners (Casas & Rascón, 2023). Standardised tests based on monolingual, neurotypical norms often underrepresent neurodivergent children and lead to misguided interventions (Uljarević et al., 2016).

It is therefore essential to distinguish language-learning difficulties from neurodevelopmental traits. Speech impulsivity in ADHD may resemble poor L2 grammar, while echolalia in ASD can be mistaken for language delay (Geurts & Embrechts, 2008; Norbury & Sparks, 2013). Teacher training grounded in neurodevelopmental understanding can prevent such misinterpretations, especially in early bilingual settings (Yoro et al., 2020; Justus et al., 2025).

Neuroeducation research supports multisensory, embodied pedagogies that use movement, rhythm, and touch to enhance comprehension and memory in learners with atypical connectivity (Barsalou, 2008; Glenberg & Gallese, 2012). Bilateral and cross-lateral activities can strengthen interhemispheric coordination and support language learning in children with ADHD and ASD (Harris et al., 2018; Travers et al., 2015).

Inclusive bilingual education should adopt whole-brain, developmentally sensitive approaches that foster metalinguistic awareness, flexibility, and social communication (Pliatsikas, 2020; Carballo & Portero, 2018).

4. Innovation Proposal: Bilateral Integration Programme for Early Years Learners

4.1. Rationale and Design of the Programme

As previously discussed, neuroscience offers valuable insights into how learning processes can be optimised through evidence-based, developmentally informed teaching. These findings are particularly relevant within CLIL settings, as they illuminate the cognitive and linguistic demands placed on young bilingual learners. Building on this framework, the programme presented here has been designed to integrate short, daily bilateral warm-ups that strengthen EFs and promote classroom readiness in early primary education.

The proposal emerges from the intersection of neuroscience, bilingual education, and inclusive pedagogy, addressing the need for practical, classroom-based tools that enhance attention, self-regulation, and engagement. Although Spain's LOMLOE (Ley Orgánica 3/2020) promotes inclusive education, many schools still lack evidence-based tools to translate this principle into daily practice, particularly in early bilingual contexts. The programme therefore offers a practical, low-preparation tool to strengthen classroom participation and provide equitable access to learning across neurotypes.

At its core, the programme draws upon the role of the CC, the main interhemispheric bridge of the brain that integrates cognitive, linguistic, and motor processes (Van der Knaap & Van der Ham, 2011). The CC enables cooperation between the hemispheres in support of EFs, attention regulation, and working memory, all crucial for literacy, numeracy, and language learning (Diamond, 2013). Research shows that children with ADHD and ASD often present atypical development in this structure, which can interfere with self-regulation and language processing (Frazier & Hardan, 2009). Bilateral warm-ups, such as short routines involving coordinated cross-midline movements, offer a simple, evidence-based method to prepare the brain for focused, balanced learning (Dennison & Dennison, 1986; Jensen, 2005).

Brief daily sessions of 10–15 minutes, enhance attention, motivation, and emotional regulation by linking motor and cognitive systems (Jensen, 2025; Boyle, 2007). Designed to be inclusive and non-verbal, they particularly benefit neurodivergent pupils aged five to six, when EFs are especially malleable (Zelazo et al., 2016). Early intervention at this stage fosters lasting gains in academic and social readiness and prepares learners for CLIL contexts requiring dual cognitive and linguistic processing (Coyle et al., 2010).

While earlier initiatives such as Brain Gym (Dennison & Dennison, 1986) or Tools of the Mind (Bodrova & Leong, 2007) have explored the links between movement and cognition, none have explicitly embedded bilateral CC stimulation within bilingual or CLIL-based frameworks. The proposed programme fills this gap by providing a scaffolded sequence of warm-ups aligned with the inclusive and competence-based objectives of LOMLOE (2020) and the European Education Area 2025 (European Commission, 2020). These frameworks emphasise

multilingualism, equity, and the development of transversal competences essential for lifelong learning.

The innovation also supports the European Agency for Special Needs and Inclusive Education's (2019) call for universal learning strategies that benefit all children while offering additional scaffolding for those with specific needs. As CLIL methodology requires simultaneous processing of subject content and an additional language, it imposes high demands on attentional control, cognitive flexibility, and working memory (Coyle, 2007). For children with ADHD or ASD, such tasks may prove overwhelming unless adequate preparatory routines are provided (Casas & Rascón, 2023). Daily bilateral warm-ups serve as cognitive and emotional bridges, facilitating readiness for demanding bilingual tasks.

The programme runs across one full academic year and consists of 185 unique 15-minute sessions, each comprising three structured activities that stimulate interhemispheric communication. Four core components guide its design: bilateral coordination, rhythm, cross-lateral integration, and embodied cognition. Tasks evolve gradually from simple mirrored actions to complex, symbolic, and creative routines. Over time, children practise a range of tasks such as table tapping, mirror drawing, infinity tracing, clap-stomp rhythms, and partner mirroring games. The progression follows a ten-month scaffolded sequence in which early months emphasise coordination and rhythm, while later stages progress towards imaginative and collaborative exercises.

The sessions are intentionally non-verbal, allowing full participation regardless of linguistic ability or neurotype. Their structure is flexible, easily adapted to different class sizes, time constraints, and ability levels. Teachers act as facilitators, modelling movements, encouraging creativity, and supporting peer collaboration.

Beyond motor coordination, the activities nurture communication, teamwork, and emotional balance, which are transversal competences essential for success in bilingual education (OECD, 2019). Warm-ups are implemented before high-load subjects such as literacy, mathematics, or L2, helping children begin lessons with focus and calm. Evidence confirms that brief, structured movement enhances readiness and reduces behavioural disruptions (Diamond & Ling, 2020; Jensen, 1998).

4.2. Implementation, Competences, and Evaluation

In addition to its pedagogical rationale, the programme explicitly advances the core competencies defined in LOMLOE (2020) and the European Framework of Key Competences for Lifelong Learning (Council of the European Union, 2018). These encompass linguistic, cognitive, personal, and cultural dimensions developed through structured physical and reflective engagement. The programme not only supports literacy and language awareness but also contributes to digital, civic, and entrepreneurial competences by strengthening foundational abilities such as attention, sequencing, and collaborative problem-solving (Table 1).

LOMLOE Competence	EU Key Competence	Programme Contribution with Justification
CCL Competencia en comunicación lingüística	Literacy competence	Though non-verbal, daily warm-ups enhance auditory processing, sequencing, and symbolic representation. Activities such as mirror drawing and following oral instructions indirectly prepare children for reading and writing (Jensen, 2005).
CP Competencia plurilingüe	Multilingual competence	Embedding the routines into CLIL lessons supports metalinguistic awareness, as verbal classroom cues are paired with non-verbal tasks. This raises sensitivity to language use and code switching in bilingual settings (Coyle et al., 2010).
STEM Competencia matemática y competencia en ciencia, tecnología e ingeniería	Mathematical competence and competence in science, technology, and engineering	Bilateral routines strengthen sequencing, pattern recognition, and spatial reasoning, laying neural foundations for numeracy and early STEM learning (Harris et al., 2018).
CD Competencia digital (indirect)	Digital competence (indirect)	While not digital in themselves, warm-ups promote visual motor integration and sequencing, core to multimodal literacy. Teachers may model activities via ICT tools, linking with CLIL's digital dimension (Coyle et al., 2010)
CPSAA Competencia personal, social y de aprender a aprender	Personal, social and learning to learn competence	Structured routines foster self-regulation, working memory, and autonomy. Peer mirroring and reflection icons encourage empathy, collaboration, and metacognitive awareness. (Diamond & Ling, 2020).

CC Competencia ciudadana (indirect)	Citizenship competence (indirect)	Group synchrony, turn-taking, and shared routines promote school coexistence (convivencia escolar) and respect for rules, providing a foundation for civic responsibility (OECD, 2019)
CE Competencia emprendedora (indirect)	Entrepreneurship competence (indirect)	Creative tasks, such as inventing bilateral routines, foster initiative, imagination, and persistence, early entrepreneurial skills of turning ideas into action (OECD, 2019)
CCEC Competencia en conciencia y expresión culturales	Cultural awareness and expression competence	Rhythmic and symbolic tasks support embodied creativity, inclusivity, and cultural expression, allowing all children to explore identity through movement and art (OECD, 2019)

Table 1. Alignment of the programme with LOMLOE and EU key competences

Each session follows a three-part structure combining focus, rhythm, and creativity. The example below illustrates the design of the first session.

Sample session

Day 1 - Introduction to Bilateral Warm-Ups

Tasks:

1. **Both-Hand Table Taps (simultaneous):** Children sit at their desks. They place both hands flat on the table and tap them together at the same time in a steady rhythm, following the teacher's lead.

Purpose: To establish group synchrony, bilateral awareness, and rhythm.

2. **Finger Thumb Rings (index to pinky, both hands):** Children touch the tip of their thumb to each finger in turn (index, middle, ring, little), forming little "rings." Both hands move in synchrony.

Purpose: To develop fine motor control, sequencing, and attention.

3. **Mirror Drawing Straight Lines:** Each child holds a pencil in each hand. They draw vertical straight lines down a page, both hands moving together in mirror form.

Purpose: To introduce mirror symmetry and bilateral fine motor practice.

Materials: Paper, pencils, clay, and classroom space.

Benefits:

- It supports bilateral coordination and early cross-lateral awareness.
- It develops fine motor skills and focus.
- It establishes cooperative group rhythm from the first session.

Key Competences (LOMLOE):

- **CPSAA:** Bilateral awareness, sequencing, attention.
- **CMCT:** Fine motor control, pattern recognition.
- **CEC:** Body expression through drawing.

Evaluation is embedded within the programme's daily and monthly cycles of practice, in line with LOMLOE (2020) and Real Decreto 95/2022, which emphasise formative assessment and individualised observation. Assessment operates at three levels: student learning, self-evaluation, and overall effectiveness. Teachers complete brief monthly checklists on coordination, rhythm, attention, and motivation to monitor progress and identify areas needing support.

Children also engage in simple self-evaluation using a colour-based reflection to express how they felt about each session, fostering metacognitive awareness and emotional regulation (Education Endowment Foundation, 2025). Short peer and group reflections further reinforce communication and empathy.

At the end of the school year (Day 185), pupils collaborate to design and perform their own bilateral routine, demonstrating autonomy, creativity, and mastery. Teachers use a summative checklist to evaluate coordination, focus, and innovation, while a final review records feasibility, engagement, and observed impact on classroom climate.

In sum, the Bilateral Integration Programme offers a concrete, inclusive model for linking neuroscience with classroom practice. It is low-cost, adaptable, and grounded in universal principles of learning that benefit all children, particularly in bilingual and CLIL contexts where attention, regulation, and language interact. Through rhythm, movement, and embodied cognition, it bridges research and pedagogy, helping classrooms become linguistically rich, emotionally balanced, and neurologically responsive.

5. Conclusions

Learning in the early years is dynamic and multisensory, with cognition, emotion, language, and movement developing in close interaction. In bilingual and CLIL settings, this interplay is particularly significant, as children must coordinate content learning with an additional language while developing EFs such as attention, working memory, and self-regulation.

The Bilateral Integration Programme translates neuroscientific insights into practical classroom strategies through short, daily routines that stimulate interhemispheric communication and prepare both neurotypical and neurodivergent learners for cognitively

demanding lessons. The programme promotes equity and classroom readiness, aligning with the competence-based principles of the *LOMLOE* and European education frameworks.

Theoretical and preliminary evidence indicate strong potential, though classroom implementation remains the next essential step. Pilot studies should examine feasibility, effects on attention and regulation, and adaptability across diverse contexts. With sustained teacher training and contextual flexibility, this innovation could provide a scalable and sustainable means of enhancing EF and bilingual learning in early education, creating classrooms that are both evidence-based and inclusive.

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