https://www.sworldjournal.com/index.php/swj/article/view/swj31-04-050
DOI: 10.30888/2663-5712.2025-31-04-050

NEUROEDUCATION AND BILINGUALISM: HOW LEARNING IN TWO LANGUAGES INFLUENCES A CHILD'S BRAIN DEVELOPMENT

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Abstract. *The article focuses on how bilingual learning impacts child brain development in the context of neuroeducation, exploring the neurobiological mechanisms involved in the perception and processing of language signals during early childhood. The aim of the study is to examine the factors that influence the effectiveness of language acquisition in bilingual settings and to investigate the development of brain structures responsible for language and their sensitivity to linguistic stimuli in the first months of life. The research applied general scientific methods of cognition: observation, analysis, induction, deduction, generalization; as well as neuroimaging techniques, including functional magnetic resonance imaging (fMRI). The results show that language processing in the infant brain is activated much earlier than previously assumed and begins forming within the first months of life. In particular, it has been found that by the age of six months, language-specific areas of the cerebral cortex become active, including the superior temporal gyrus (STG), which is involved in phonetic processing. This suggests that language perception relies on innate, neurobiologically driven mechanisms rather than solely on learning or social environment. The observed early activation indicates that the infant brain is functionally ready to process sounds from the first weeks of life, which provides the foundation for developing language competence in a bilingual environment. The study also demonstrates that activation of Broca's area (LIFC), which plays a central role in semantic processing, occurs at around 10 to 14 months of age. This stage aligns with the emergence of the first meaningful language units in children growing up in bilingual settings. These findings challenge the view that language acquisition depends solely on general perceptual mechanisms; instead, the conclusion is drawn that language development is determined by the functioning of specialized brain structures that are active even before speech production begins. The practical value of the study lies in establishing scientifically informed approaches to early bilingual education and in developing effective educational strategies that take into account the neuroplasticity of the child's brain.*

Keywords: *bilingualism, infants, neuroeducation, language processing, brain development.*

Introduction

For nearly a century, parents, educators, and researchers have expressed conflicting views on bilingual child development. This phenomenon is so widespread that the term "bilingual paradox" has emerged in academic literature [7-8]. Modern empirical studies indicate that children can successfully acquire two or more languages from an early age, provided there is consistent linguistic exposure. At the same time, skepticism about early dual-language exposure persisted in scholarly discourse just two or three decades ago, and some researchers still support this perspective today. The belief that early bilingual environments can be harmful remains influential in both educational practice and among parents raising children in multilingual settings. Arguments supporting this viewpoint often invoke the concept of "language contamination," which, according to J. Crawford, allegedly results from early contact with a second language [1]. Research findings have influenced the field of education. In the United States, for example, a dominant belief in many schools is that early instruction in a second language – or the simultaneous acquisition of two languages, such as English and Spanish – might negatively affect proficiency in the majority language (in this case, English). This view has shaped educational policy, often delaying second language instruction until middle or high school – after the critical period for language development has passed [7]. As a result, in several U.S. states (such as Massachusetts), language policy underwent changes that gradually removed Spanish from public school curricula for children from Spanish-speaking families, replacing it with English-only instruction. Outside the school environment, similar beliefs influence family language strategies: parents often choose to temporarily limit the use of one language, believing it is better to ensure full mastery of one language before introducing another in order to avoid language confusion. Another common concern is that early bilingual exposure might lead to insufficient mastery of both languages compared to children raised in monolingual households [8].

It is important to emphasize that these concerns mainly relate to the early developmental period, when a child's language system is still forming and remains highly sensitive to environmental influences – typically before the age of three. At the same time, there is broad scientific consensus that learning foreign languages later in life – during adolescence, adulthood, or even old age – has a positive impact on cognitive development. Studies confirm that acquiring additional languages helps preserve neuroplasticity, enhances memory, attention, cognitive flexibility, and reduces the risk of cognitive decline in older age.

In order to clarify the reasons behind the prevalence of cautious views on early bilingual exposure, this research focuses on the outcomes of simultaneous dual-language acquisition in young children. Two hypotheses are presented in this study, each representing opposing interpretations of the so-called "bilingual paradox."

The first hypothesis suggests that early exposure to two languages positively influences the development of language competence and supports overall cognitive growth. The second hypothesis, in contrast, argues that early bilingual environments may have a disorganizing effect, slowing both language and intellectual development compared to children raised in monolingual settings.

Literature Review

The question of how bilingual learning influences a child's brain development has been extensively examined in international academic literature. This study considers the work of scholars such as I. Kovelman, S. Baker, and L. Petitto [6], who, using functional MRI, show that bilingual children activate broader areas of the brain during syntactic language processing, suggesting the existence of a unique "neural signature" of bilingualism. This conclusion is further supported by the collaborative research of L. A. Petitto and K. Dunbar [8], who explore not only language processing but also the broader educational context in which the bilingual brain is shaped.

Early stages of language development were studied by P. Jusczyk [5] and J. Crawford [1]. Research by W. Redlinger and T. Park [9] complements this picture by examining language mixing in children growing up in bilingual environments. J. Werker and R. Tees [10] demonstrated that the ability to distinguish non-native speech sounds diminishes with age, which is important for understanding critical periods in language development. Meanwhile, M. Dubins [2], using fNIRS technology, investigates early phonetic processing in infants' brains and finds that even at a few months old, bilingual children show different patterns of brain activity compared to monolinguals. The studies of K. N. Dunbar and J. A. Fugelsang [3] examine changes in conceptual thinking from the perspective of cognitive science, emphasizing that bilingualism can foster more flexible mental models of the world.

Despite the wide range of literature on this topic, there is a noticeable lack of systematized material that comprehensively addresses the neuropsychological effects of bilingual education. For this reason, information was analyzed, grouped, and organized using various methods of scientific inquiry, and presented within the context of the research topic.

Purpose of the article

The aim of the article is to analyze the factors that determine the effectiveness of early language acquisition, to clarify the mechanisms of brain development in the context of bilingual education, and to explore the sensitivity of specific brain areas to particular language signals during the first weeks and months of life.

Research results

One of the first researchers to investigate the influence of a bilingual environment on child brain development was F. Genesee, who in 1989 classified two hypotheses: 1) the "single language system" hypothesis and 2) the "separate language systems" hypothesis [4].

According to the first, during the early stages of language development, children exposed to two languages do not distinguish between them, forming a single fused language representation. Within this framework, it is assumed that conscious language differentiation occurs around the age of three [9]. In this context, the hypothesis proposed by P. Jusczyk [5] is relevant; it suggests that language processing in infants does not begin with word comprehension, but with the use of general perceptual mechanisms – meaning the child initially just hears and distinguishes sounds without linking them to specific meanings. Only later, when the brain identifies patterns in adult speech, do these sound signals become associated with meaning and evolve into true linguistic perception. In this way, the child moves from passive listening to active language understanding. Accordingly, this initial fused language repertoire may lead to delayed language development compared to monolingual peers. For nearly two decades, this hypothesis dominated scientific discourse and significantly influenced educational policy. Under this approach, it was assumed that children learning two languages simultaneously do not differentiate them in the early years, which results in slower speech development and signs of delay.

In contrast, the separate language systems hypothesis asserts that bilingual children are able to differentiate between the two languages they are exposed to from an early age [4]. However, the exact age at which this differentiation occurs remains unclear, as the three-year benchmark is conditional and varies according to individual developmental characteristics [7].

Today, cognitive neuroscience has made significant progress in studying the brain organization underlying language processing in bilingual children. Several key brain areas have been identified as responsible for core cognitive functions essential to language acquisition: including short-term and long-term memory, attention control, analogical reasoning (the ability to identify similarities and correspondences), deductive reasoning (drawing logical conclusions from general premises), causal reasoning (establishing connections between events), as well as the processing of linguistic structures and semantic integration. The active engagement of these neural systems indicates the high plasticity of the child's brain, which enables effective adaptation to a multilingual environment [8].

These cognitive processes form the foundation of scientific thinking and reasoning, and therefore serve as the basis for educational neuroscience, which focuses on exploring learning mechanisms in the context of science education [3]. Thanks to advances in cognitive science and neuroimaging, as described in the 2007 work of K. Dunbar, J. Fugelsang, and C. Stein, it has become possible to study the cognitive and neural changes that accompany the learning process, which is directly relevant to the optimization of pedagogical strategies [3].

To better understand the neural basis of early language development, a study of brain activity in infants from the second day after birth has been planned. The goal is to identify the mechanisms of language processing in both monolingual and bilingual environments. This approach became possible due to modern technologies in cognitive neuroscience, particularly Near-Infrared Spectroscopy (NIRS). This technique enables visualization of brain activity by measuring changes in blood oxygenation in the cerebral cortex—a marker reflecting the level of neural activity. Thanks to its non-invasive nature, NIRS has made it possible to examine language processing in infants for the first time without posing any risk to their health. These studies aim to answer the following questions:

a) what factors determine the effectiveness of early language acquisition;

b) how the development of relevant neural structures takes place;

c) how sensitive these structures are to specific language signals during the first weeks and months of life.

The research results show that a key factor in early language acquisition is the presence of biologically determined specialized brain areas that become active even before the first words appear. For example, activity in the Superior Temporal Gyrus (STG) – the region responsible for phonetic processing—can already be observed in infants between two and six months old. This indicates an innate ability for phonetic-level language perception, regardless of whether the infant is bilingual or monolingual [7].

Another important factor is the language environment. Studies demonstrate that both bilingual and monolingual children focus on their native language at roughly the same age, pointing to a universal timeline of language perception development in infants, independent of the number of languages they are exposed to [2].

A third key factor is sensitivity to phonetic contrasts across languages. Up to approximately 14 months of age, infants can distinguish sounds not found in their native language, but this ability diminishes over time, underscoring the importance of early language experience [10].

Therefore, the effectiveness of early language acquisition is determined by the presence of biologically active language areas in the brain, the nature of the language environment, and the infant's sensitivity to phonetic differences in the first months of life.

The development of language-related brain areas occurs gradually and is closely linked to the achievement of key language milestones in child development. fNIRS studies have shown that from as early as 2 to 6 months of age, the STG is already functioning actively in phoneme perception. This confirms that phonological processing has a biological foundation and emerges prior to semantic processing [7].

Another critical brain area – Left Inferior Frontal Cortex (LIFC), or Broca's area – is activated much later, around 10 to 14 months of age. It is associated with semantic word processing and likely regulates the stage at which a child begins producing their first words [2]. This means that the development of language regions in the brain follows a sequential path: the area responsible for phonetics is activated first, followed by the area responsible for semantics.

These brain changes are associated not only with age but also with the achievement of specific psycholinguistic milestones, directly demonstrating the neuroplasticity of the brain in early childhood.

Studies indicate that the language-related areas of the infant brain are highly sensitive to linguistic signals from the earliest months of life. In particular, the STG shows strong activation in response to linguistic, but not non-linguistic, stimuli—even in the youngest infants (2–6 months) – highlighting this region's early specialization for phonetic processing [7].

This is further supported by studies comparing responses to linguistic and non-linguistic (tonal) sounds. Both adults and infants exhibit left-hemispheric brain activation when perceiving speech phonemes, but not when hearing non-linguistic tones [2]. This indicates that the brain has a specific sensitivity to linguistic signals, not merely to the acoustic features of sounds.

These results contradict the hypothesis proposed by Jusczyk [5], which claimed that language processing in infants begins with general perceptual mechanisms and only gradually becomes language-specific. On the contrary, fNIRS data show that language processing is specialized from the very beginning, supporting the existence of innate language mechanisms.

To trace the trajectory of bilingualism from early childhood to adulthood, researchers examined how the age of first exposure to a second language influences the neural organization of language processes. Special attention was given to identifying differences in brain activity between bilingual and monolingual individuals and to investigating the possible existence of specific "neural signatures" of bilingualism. In addition, the impact of linguistic characteristics of the acquired languages on brain organization was considered.

To conduct the analysis, Petitto, L. A., and Dunbar, K. N. applied the following methods:

- functional Magnetic Resonance Imaging (fMRI), which makes it possible to visualize active brain regions during specific cognitive tasks;
- functional Near-Infrared Spectroscopy (fNIRS), which captures changes in brain blood flow as an indicator of neural activity.

These methods enabled a detailed study of the neural processes taking place in bilingual individuals while perceiving and processing each language, as well as when switching between language systems. The results of the study are summarized in Table 1.

Table 1 – Results of the study on the influence of a bilingual environment on a child's brain

Topic	Content
Early and late language exposure	Adults who were exposed to two languages early in life (before age five) process languages similarly to monolinguals: classical language areas in the left hemisphere are activated without excessive involvement of other brain regions. Those who learned a second language later show greater bilateral activation and require more cognitive effort.
Comparison of bilingual and monolingual brains	Bilingual individuals exhibited a higher increase in blood oxygenation during English language processing compared to monolinguals. This may indicate the presence of a specific "neural signature" of bilingualism.
Influence of language structure	Neural differences were identified in bilingual individuals that align with grammatical and morphological distinctions between Spanish and English.
Brain scans of children during reading	Brain scans of bilingual children revealed activation patterns reflecting the processing of deep (English) and shallow (Spanish) orthographies. Enhanced bilateral activation in the inferior frontal cortex was also observed, associated with dual lexical access. This supports the hypothesis of a "bilingual signature."

It is important to emphasize that early bilingualism significantly enhances learning effectiveness by improving reading skills. Studies have shown that Spanish-English bilingual children who began learning both languages simultaneously before the age of three achieved the highest reading performance in both languages by second or third grade.

Equally important are findings demonstrating that reading skills can improve even in children exposed to bilingualism at a later age. The type of instruction plays a crucial role: for instance, children from English-speaking families who attended bilingual schools (English-Spanish 50/50) outperformed their peers from monolingual English schools in tasks involving phonemic awareness. This indicates that even monolingual children can gain educational advantages from learning in a bilingual environment, as confirmed by the 2008 study conducted by I. Kovelman, S. Baker, and L. Petitto.

As a result, recent empirical studies challenge the previously widespread belief that early exposure to two languages leads to delayed language development or language confusion. At the same time, these studies also question the opposing hypothesis, which holds that learning a second language at a later developmental stage is more appropriate. Proponents of this view argue that acquiring a second language later does not significantly affect a child's ability to learn it, and therefore, neural mechanisms do not play a decisive role in the process. This position is often supported by examples of adults successfully attending language courses (e.g., Japanese) and achieving conversational competence. Based on such examples, the conclusion is drawn that there is no critical or sensitive period for learning a second language, unlike the acquisition of a first language in early childhood.

Based on an analysis of current research, it can be concluded that supporters of early second language introduction justify their position by pointing out that young children perceive both languages equally without favoring one over the other. This is explained by the fact that at the initial stage of language development, children respond not to meaning, but to the acoustic features of speech. As P. W. Jusczyk [5] suggests, language processing begins with general perceptual mechanisms, and only later do sounds take on meaning for the child. However, since the transition from sound recognition to word comprehension takes time, unstructured exposure to two languages may cause temporary confusion. The child may not yet clearly distinguish which language system a particular word belongs to, complicating the process of language consolidation.

At the same time, research shows that introducing a second language at an early – but not too early – age, when the first language has already been partially acquired, can also be effective. This approach does not require the activation of specific neural mechanisms typical only of infancy. Thus, gradually introducing a second language during a more stable phase of speech development helps avoid cognitive confusion while still enabling successful second language acquisition.

Within this framework, a common educational practice is based on the belief that children from homes where a different language is spoken (e.g., Spanish) should first develop a linguistic and cognitive foundation in the country's official language (e.g., English), postponing the learning of their native language to a later stage. The assumption is that once English is acquired, systematic instruction in the second language – in this case, Spanish – can begin through reading and academic study. This is associated with the fact that childhood bilingualism in real life rarely has a balanced and symmetrical character. Migration, socio-political conditions, and educational reforms often result in children entering new language communities at varying ages – sometimes not until adolescence – which adds extra challenges to language adaptation.

Conclusions

Brain scan data show that language processing in infants begins much earlier than previously believed. Specifically, activation of language-specific areas, such as the Superior Temporal Gyrus (STG), responsible for phonetic processing, can already be observed before six months of age, confirming the existence of innate, neurobiologically determined mechanisms for language acquisition. Activity in Broca's area (LIFC), associated with word meaning comprehension, appears later— around 10 to 14 months – and correlates with the emergence of a child's first words. This means that language acquisition is not based on general perceptual mechanisms for understanding words, as some researchers have assumed, but on specialized brain structures that are active from the earliest stages of life and rely on sound perception. Infant language sensitivity also shows selectivity: even in the youngest children, there is a functional distinction between processing linguistic and non-linguistic signals.

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