

Music and Brain Plasticity: An Innovative Approach to Supporting Dyslexia

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Abstract

Over the past few decades, research has revealed that nearly one-third of the population experiences significant reading and writing difficulties, hindering their educational and professional trajectories. In 2012, the PISA assessment highlighted a decline in the performance of 15-year-old students within the French educational system. To address this issue, several experimental programs were developed, including a music-and-language approach focused on leveraging neuroplasticity to enhance learning and support dyslexia management.

Advances in neuroscience, psychology, and cognitive science have significantly improved our understanding of neuroplasticity. Within this context, recent research has established music as a powerful tool for brain development. Studies on the "musical brain" demonstrate that music - capable of stimulating global cerebral activity - engages the entire brain through complex auditory and emotional processes, justifying its description as "food for neuroscience." Consequently, neuroimaging studies show that musical practice structurally modifies the brain (specifically the auditory, somatosensory, and motor cortices) in children, increasing gray matter volume and improving white matter organization. This cortical and subcortical reorganization directly influences other cognitive functions, particularly language, as both domains share overlapping neural resources and contribute to alleviating dyslexia symptoms.

This article aims to clarify the cerebral mechanisms involved in music learning and its educational benefits. After reviewing general brain functioning, we discuss findings related to neuroplasticity in musicians and examine the transferability of music-induced changes to cognitive and language functions. Finally, we address the role of music in supporting language learning among children, with a specific focus on phonological skills in children with dyslexia.

Keywords: Cognitive development; musical training; neuroplasticity; language; dyslexia

Introduction

For decades, the human brain - specifically the upper cerebrum [1] - was viewed as a mosaic of independent cortical regions, each characterized by a specific function that structures the organ. Historically, it was hypothesized that these modular functions were housed across both hemispheres, and that developing a particular faculty would result in the structural enlargement of the corresponding brain area, potentially inducing specific

cranial alterations [2-4]. This localized view of brain function was supported by Fodor's modularity of mind theory (1983), which posits that the brain consists of autonomous, independent modules, each akin to a specialized computer program processing information within its own encapsulated database [5]. Thus, complex cerebral functions, such as music or language learning, are conceptualized as modular systems composed of structured sub-modules organized hierarchically, where each processes specific

inputs before transmitting them to a higher level [6]. Nevertheless, overall brain function relies on information stored across the entire system, suggesting a high degree of interdependence, particularly within cognitive functions such as attention and memory [7]. This functional integration was further supported by the work of Park and Friston (2013) [8], who proposed the integration of distinct localized modules with specialized functions contributing to a single, defined task. Consequently, a comprehensive system like language would engage multiple specialized modules, including auditory perception, characterization, attention, memory, and emotion [9].

In practice, these local and global systems operate as neural networks characterized by their intrinsic interconnectivity [2]. Short-range connections typically support specialized processing, whereas long-range connections are involved in high-level cognition, operating at an integrated or global level [10]. Cerebral processing is therefore based on a set of specialized neural micro-networks integrated globally through an interactive and dynamic interconnectivity of axonal fibers, which ensures simultaneous neuronal parallel processing [11,12]. Recently, this operational model has been confirmed by *in vitro* studies on commercially available neuronal cell lines used for therapeutic trials of brain disorders, and further supported by electrophysiological recordings [13]. Additionally, Rester et al. (2024) [14] demonstrated a precise adjustment of cerebral blood flow in response to local increases in neuronal activity. Nevertheless, the global processing underlying general cognitive functions enables a single structure to perform multiple roles, just as a single activity can engage multiple structures. This mechanism explains the wide spectrum of cognitive functions managed by the brain, despite its fixed morphology within the cranium and its relatively constrained size [7,15,16]. Advances in neuroscience have confirmed this connectionist and dynamic model of the brain [2,3], wherein the discovery and characterization of neuroplasticity have proven fundamental. Neuroplasticity represents the brain's ability to continuously remodel its own anatomy and functionality in response to experience [7]. While the brain is shaped by experience throughout the lifespan, it remains highly receptive during early development; this property allows for targeted modulation and structural modification through training [17]. Because cerebral areas are highly interconnected, interdependent functions naturally influence one another. Consequently, learning within a specific domain can generalize to another domain that shares, at least partially, the same neural network. This transfer of learning can thus span across distinct disciplines [2,7,17].

Among the mysteries of the human brain, one question has long haunted scientists, educators, and philosophers alike: how and why did evolution endow our brain, among all its remarkable faculties, with the capacity for musical art? Furthermore, what drives this tendency to utilize rhythm and melody to interact with others - whether a mother with her infant, a dancer with their partner, a priest with his congregation, a soldier in a military parade, an orchestra with its audience, or participants at a rave? Advances in neuroscience have begun to provide answers to these age-

old questions, demonstrating with increasing precision that our brain is actually an eminently musical organ. It houses thousands of neural resonators - veritable rhythm generators permanently driven by oscillatory activity. It is precisely by synchronizing with this oscillatory activity of neural networks that speech and music acquire their full meaning. Through this synchronization, we communicate with others, transforming the brain into a fundamentally social tool. Finally, by acting upon this very rhythmic activity, musical practice is capable of treating various cerebral dysfunctions and impairments across the lifespan, from childhood to old age. This therapeutic potential is being increasingly demonstrated by modern medicine, particularly in cases of dyslexic disorders [18,19].

Consequently, the perspectives of the neurologist and the musician converge, contributing to a synthetic vision of music as a powerful instrument of connection and communication. Music is capable not only of circulating information between different areas of our own brain and between our brain and those of others, but also of repairing these neural connections when they are defective [20]. When considering music - an art form combining sound and rhythm - it remains an omnipresent element of human existence. As Marcel Proust famously noted, it offers a unique example of "what communication between souls might have been." Throughout centuries, philosophers, artists, and scientists have sought to understand the place of music within human activity, particularly its impact on emotion, cognition, and behavior [20]. The past two decades have been marked by growing interest from the brain sciences, which have famously framed music as "food for neuroscience" [21]. This neuroscientific interest is driven, among other goals, by the pursuit of identifying the neural correlates of this sensory language, which relies on temporally ordered rules of validated complexity [2,22]. Consequently, music education and instrumental practice have increasingly been adopted across all socioeconomic backgrounds as a strategy to enhance cognitive well-being and foster a more conducive environment for knowledge acquisition, particularly in youth. Furthermore, music proves to be a powerful instrument of connection and communication, capable not only of circulating information between different parts of our brain and those of others, but also of repairing these connections when they are defective [23].

This intersection between cognitive enhancement and skill development directly aligns with the broader objectives of pedagogy. Fundamentally, the teaching profession centers on transmitting knowledge to learners of all ages, from children to adults, ensuring they easily comprehend and assimilate instructional content. Globally, this process facilitates effective learning and education, adhering to a prescribed pedagogical framework that must be both efficient and high-performing [24]. To achieve relevance in this mission and master this instructional art, adapting and optimizing learning methodologies becomes imperative.

Consequently, several disciplines exploring the relationship between cognition and the brain - the central control hub for knowledge acquisition - are required. These disciplines draw heavily

from cognitive neuroscience, a field dedicated to knowledge and research regarding the nervous system [25]. Indeed, establishing links between the nervous and cognitive systems has been shown to foster the development of more efficient learning strategies. This advancement stems from the multidisciplinary nature of cognitive neuroscience, which encompasses neuro-education and neuro-pedagogy - fields that integrate psychology, neuroscience, and education. This cross-disciplinary interaction ultimately drives the emergence of innovative strategies and methodologies upon which modern teaching rests.

Within this neuro-educational framework, human biological predispositions play a crucial role. In 2007, Oliver Sacks asserted that human beings are inherently both a musical and a linguistic species [26]. With few exceptions, nearly all individuals can perceive music, including pitch intervals, timbre, tonal variations, melodic contours, and rhythm. These musical features are processed and integrated across diverse brain regions, and this analysis of perceived auditory information is frequently accompanied by intense emotional responses [27]. Building upon these intersections, the present study specifically explores the cerebral mechanisms underlying music learning and the subsequent transfer of this artistic acquisition to various aspects of language achievement. First, general brain function and learning mechanisms are presented, highlighting literature findings on neuroplasticity, particularly in musicians. Second, the shared learning mechanisms between music and language are discussed. Third, we examine the role of neuroscience in music learning and

its transfer to language learning - processes that share common neural resources in auditory perception, attention, and memory. Finally, phonological skills and their impairment in children with dyslexia are addressed.

Brain and Perception

Human beings are distinguished from other animals by their capacity to express thought and communicate through language, utilizing a system of vocal signs or speech, as well as graphic signs in written form; this collective set of functions constitutes a language that objectifies thought. When examining spoken language, it shares fundamental characteristics with music [28]. Indeed, the processing of information conveyed by language exhibits strong similarities to that of music, particularly at the sensory level, as the acoustic signals generated by both domains undergo similar cerebral analysis [29]. These acoustic signals are perceived by the ear and transmitted through the tympanic membrane to the brain (Figure 1). From a physical standpoint, sound results from the perturbation of an elastic natural medium - whether fluid or solid, particularly air - following a series of vibrations that successively strike the outer, middle, and inner ear. Within the auditory system, sound vibrations are captured by the pinna of the outer ear and travel down the auditory canal to strike the tympanic membrane in the middle ear. Subsequently, via sensory receptors sensitive to these acoustic vibrations, the inner ear transmits the perceived sensory message to the brain through the auditory nerve, where the information is ultimately interpreted (Figure 1).

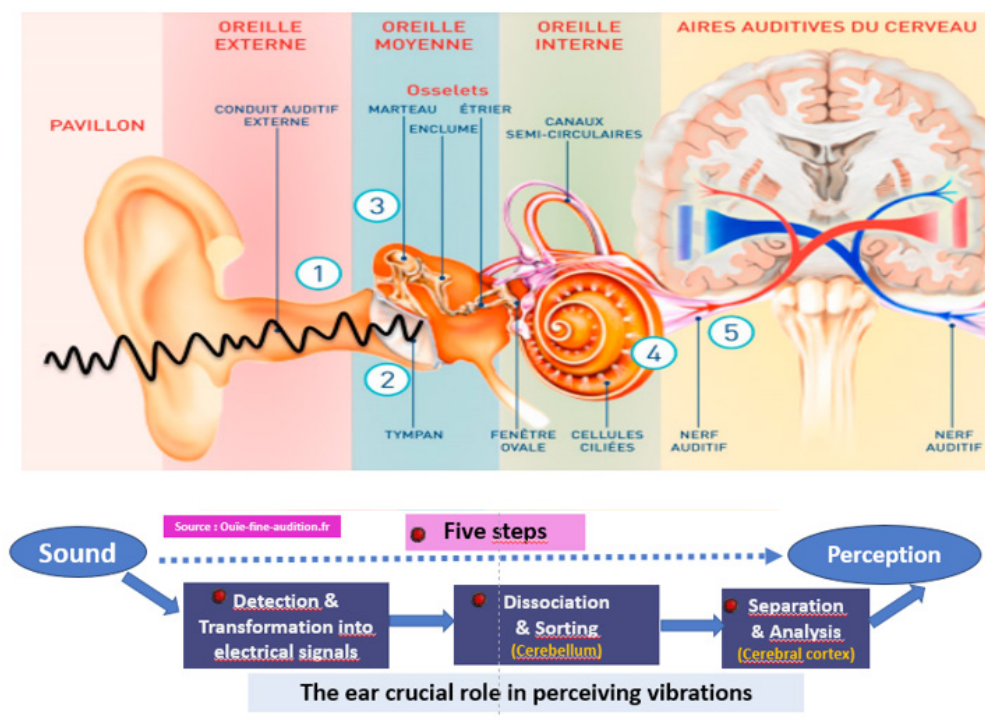


Figure 1: The five stages involved in sound perception [30].

From a cognitive perspective, language acquisition is a relatively prolonged process that develops progressively over time [31]. The language function requires motor maturation and intellectual development driven by acquired learning. In children, language development progresses through several distinct stages. It begins with reflexive crying as an expression of unmet needs, followed by cooing and babbling (around 2 months), before reaching the stage of human language learning (around 9 months). At this level, children enter the “jargon phase,” imitating the rhythm of adult sentences by repeating syllables. Pronunciation gradually improves, and vocabulary expands from 10 to 20 words at 18 months to over 200 words by 24 months. Around the age of two, children transition to the sentence stage, characterized by the use of verbs to indicate actions. Finally, the fifth stage - social language - emerges around 6 to 7 years of age, where monologues give way to genuine conversation [1].

Consequently, learning induces a reorganization of knowledge embedded within the brain, where anatomical modifications occur to optimize cognitive efficiency [32]. This highlights the critical importance of pedagogical choices and underscores the direct influence of teaching practices on the brain; considering such impact is paramount during children’s learning experiences. According to Dehaene [33], this learning process relies on four essential pillars: attention, active engagement, error feedback, and consolidation. To help students select the information to be acquired, it is necessary to capture and channel their attention. This requires identifying engaging and optimal solutions to maximize attentional focus. Attention is further driven by error feedback, which is essential for promoting learning. Indeed, this feedback enables the brain to adjust knowledge during acquisition by generating a cognitive shift

[34]. This phase is subsequently followed by consolidation, which allows for automaticity and concludes the learning process.

Different areas of the human brain are specifically recruited depending on the type of learning involved. For instance, language production is localized within Broca’s area, whereas speech sound comprehension occurs within Wernicke’s area; these two regions, typically located in the left hemisphere, enable human communication (Figure 1) [35]. Interestingly, the left hemisphere is also activated by rhythm, suggesting the potential establishment of a cognitive link between language and music. These two domains share numerous characteristic similarities, such as the anatomical structures involved and the memorization of words and sounds. Consequently, Bigand [29] conceptualized the processing of music and language as operating through highly similar mechanisms at both the sensory and cognitive levels.

Language Tasks

Language involves a multitasking process that enables individuals to evoke ideas, integrate into social life, orient themselves in both time and space, incorporate reflection, meditation, or introspection into their actions, and transform their reasoning. Linguists have characterized language through four core subfields: phonetics, semantics, syntax, and pragmatics [36]. While phonetics focuses on the study and production of all possible sounds in natural languages, semantics considers the meaning within language, and syntax analyzes word order, structure, and sentence formation. Lastly, pragmatics examines the practical use and contextualization of utterances within a language (Figure 2). Oral language develops remarkably during the first six years of life and continues to refine over many years [37].

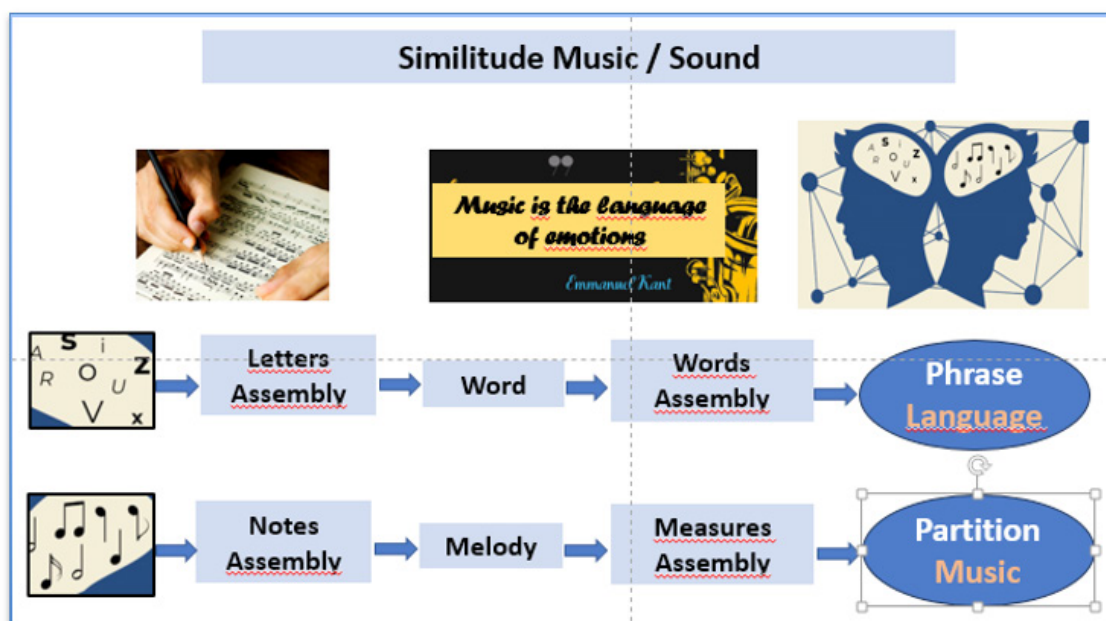


Figure 2: Music and sound conception similitude.

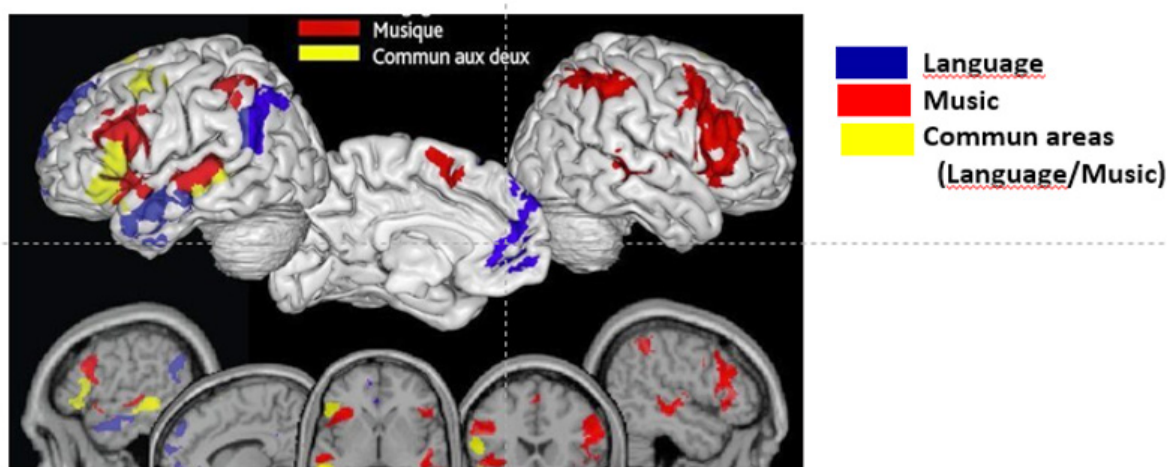
From Ear to Brain

The ear plays a pivotal role in sound perception, a function that enables humans to receive acoustic information from their surrounding environment [1]. Within this organ, sound-induced air vibrations are detected and transduced into electrical signals, which travel along the auditory nerve to the brain for analysis. These generated signals are inherently complex, characterized by their frequencies, and primarily composed of musical notes intertwined with background noise. Once these signals reach the brain via subcortical pathways, they are dissociated and sorted within the cerebral cortex, where musical pitches are reconstructed and noise components are isolated for analysis. Consequently, structural attributes such as pitch, rhythm, timbre, and intervals - as well as the perception of dissonance or consonance - are identified. This complex cerebral analysis occurs across numerous, distinct brain regions.

Engaging in music listening activates a vast network of brain areas involved in auditory perception. Given the multitude of sounds, their constituent notes, and their acoustic interference, the cortical areas involved in this perception are not strictly specific or exclusively dedicated to music or any single auditory domain. Instead, the decomposition of a sound yields simplified acoustic elements processed by distributed neural zones, regardless of the sound's origin. This phenomenon has been widely demonstrated

through functional magnetic resonance imaging (fMRI) studies [38]. The neuroscientific investigation of music's effects on the brain has been pursued for decades. In 2011, Hervé Platel (INSERM, France) investigated music perception and musical memory, mapping the cerebral networks involved in these tasks. His work demonstrated a profound interhemispheric complementarity during these functions, challenging the historical hypothesis of strict hemispheric independence [39].

Indeed, until recently, a prevalent neuroscientific assumption held that the two cerebral hemispheres operated with rigid functional independence: the left hemisphere was thought to govern concrete processes related to speech and language, while the right hemisphere was tied to abstract processes like creativity and art. However, contemporary research shows that music recruits the entire brain, engaging highly distributed functional networks [40]. This holistic view is strongly supported by Daniel Levitin [41], a neuroscientist at McGill University, who emphasized that "playing, listening to, or composing music engages nearly every area of the brain that has been identified, and involves almost every neural subsystem" (Figure 3). These diverse insights regarding sound perception and the expansive cortical recruitment required for its processing are fundamentally linked to neuroplasticity, which underlies the brain's capacity to execute such complex cognitive tasks.



Source: Science & Vie, N° 278 Hors-série (2017)

Figure 3: Common brain areas involved in language and musical activities.

Cerebral Plasticity and Its Mechanisms

Following the emergence of magnetic resonance imaging (MRI) technologies in the early 1990s, research investigating neurostructural differences between musicians and non-musicians expanded rapidly. These studies demonstrated that music learning

significantly alters both the function and structure of the brain, particularly within motor and auditory regions (Figure 3). Indeed, the brains of musicians are characterized by enlarged areas within complex motor structures, such as the corpus callosum and the cerebellum, as well as the lateral temporal cortex, where

representations of sound, speech, and music are processed and stored.

The human brain consists of peripheral gray matter, which forms the cerebral cortex, and underlying white matter, which differs in both composition and function. Gray matter houses neurons arranged within cortical gyri, whose axons extend deeper into the brain to form complex fiber tracts. Among these, the corpus callosum and the arcuate fasciculus have been extensively studied, revealing a distinctive structural development in musicians compared to non-musicians. Furthermore, both tracts are heavily involved in language processing; the corpus callosum contributes to the hemispheric lateralization of language, while the arcuate fasciculus connects posterior sensory regions of the brain to anterior motor regions, notably Broca's area, which is critical for language production and phonological processing.

At the microscopic level, intensive instrumental training is accompanied by the proliferation of glial cells - specifically oligodendrocytes - which synthesize the lipid-rich myelin sheath surrounding axons. The presence of myelin facilitates the efficient propagation of action potentials along nerve fibers, thereby optimizing information transmission between disparate brain regions. To better detect these functional differences, electroencephalography (EEG) and magneto-encephalography (MEG) have been employed to compare musicians (with over 15 years of practice) to non-musicians. These recordings revealed that the cortical representation of musical tones within the auditory cortex was significantly more expanded in musicians, particularly those who began training at an early age (around 9 years old), regardless of the instrument played, such as the violin or trumpet [42]. Similarly, Trainor et al. (2003) examined the effects of pure tones, as well as violin and piano sounds, on the auditory cortex of adults and young children (aged 4 to 5 years), both musicians and non-musicians. They concluded that the P2 component - an auditory evoked potential - exhibited a significantly larger amplitude response in trained individuals.

Specific Criteria of a Musician

Before examining the neuroplastic processes that underlie music perception, it is essential to establish how experts define a "musician" and what specific criteria are required for this designation. In theory, all human beings could be considered musical due to their innate capacity to recognize and appreciate music, with the exception of individuals affected by congenital amusia. However, to better distinguish and select professional or highly trained individuals in research, operational definitions have been established [43]. Specifically, the designation of "musician" requires the active practice of an instrument, which includes the human voice. Furthermore, a musician is operationally defined as an individual who engages in regular, sustained musical practice for a minimum duration of ten years. This criterion effectively separates trained musicians from non-musicians, who possess either no formal, sustained musical training or relatively little. In line with these criteria, Platel and colleagues [39] identified distinct structural differences between the brains of musicians and non-

musicians using magnetic resonance imaging (MRI). The brain reorganizes and modifies itself in response to training and acquired musical experience, leveraging its capacity for neuroplasticity. Consequently, a musician's brain becomes morphologically distinct from that of a non-musician, exhibiting structural, functional, and cognitive adaptations. As researchers have noted, the musician's brain is literally shaped by learning and practice, involving multiple regions.

MRI studies consistently highlight adaptations in the auditory cortices - which primarily receive sound input across both the left and right temporal hemispheres - as well as in motor regions responsible for instrument mastery [44]. These regions exhibit significantly more advanced electrical and metabolic responses in trained individuals. This specificity stems from neuroplasticity, which promotes an active engagement with music rather than a passive listening attitude. In fact, the total hours a musician dedicates to playing an instrument often exceed several thousand. During these periods of musical practice, musicians develop and refine diverse motor skills characterized by speed and precision. This is achieved through the motor coordination, synchronization, and functional independence developed between both hands, as well as the visuomotor skills required for accurate sheet music reading. Furthermore, in the auditory domain, musicians acquire a heightened sensitivity to pitch accuracy and the timbral quality of the produced sound. Other domain-general cognitive functions are similarly enhanced through musical practice, including memory, attention, spatial orientation, and temporal synchronization.

The acquisition of these multifaceted skills results from modifications in the underlying neural substrates within the involved brain areas. These regions undergo structural development in response to the repetitive practice essential for the refinement of a true musician's abilities [43]. These neural circuits have been extensively investigated by neuroscientists aiming to map the brain networks involved, successfully demonstrating structural and functional changes within these specific areas in practicing musicians [45]. All of these cerebral modifications observed in practicing musicians are recognized as the direct result of neuroplasticity, occurring as a function of sustained training undertaken by an active instrumentalist. Our understanding of this malleable nature of the brain - susceptible to being reshaped by long-term instrumental practice and retaining these adaptations for future cognitive benefit - has significantly evolved over time.

Historical Overview of Brain Plasticity

Historically, neuroscientists first focused on induced cerebral plasticity within the motor system resulting from musical practice. It was observed that the cortical area corresponding to hand movements, located in the motor cortex, was more developed in pianists compared to control subjects (non-musicians). To investigate the effects of bimanual practice, the brains of pianists - which require fine motor control of the fingers of both hands - were compared to those of violinists, whose hand usage is highly asymmetrical. Indeed, while the fingers of the violinist's left hand must be positioned rapidly and with extreme precision on

the strings, the right hand is primarily restricted to holding and managing the bow. Anatomically, comparing the motor cortex of pianists, violinists, and non-musicians revealed an increase in cortical volume within the zones controlling finger movements in musicians [20]. Because this cortical growth occurs within a cranium of limited capacity, it results in a more pronounced folding of the central sulcus as well as the pre- and post-central gyri.

In pianists, this volume increase is noticeable in both the left and right motor cortices, whereas in violinists, it is only visible in the right motor cortex, which controls left-hand activities. Similar modifications have been noted in the somatosensory cortex, which underlies the enhanced sensory feedback acquired by musicians, such as the refined tactile sensitivity of a pianist's fingers and the mastery of vibrato in violinists [46]. Somatosensory cortex activation was also investigated by successively stimulating the fingers with trains of vibrations. Such stimuli triggered a significantly more pronounced cerebral response in musicians than in non-musicians. The magnitude of this response in the right hemisphere was particularly characteristic of violinists, reflecting the heightened sensitivity acquired through practice [46].

Around the same period, the coordination of sensorimotor processes in the fingers of professional musicians was investigated [47]. To execute the specialized and distinct tasks of each hand - each controlled by the opposite hemisphere - precise task coordination is required. This necessitates a massive and organized transmission of information from one hemisphere to the other, enabling the seamless harmonization of the musician's bimanual movements. Indeed, along the auditory pathways leading to the cortex, a small structure called the inferior colliculus exhibits intense activity modifications resulting from musical practice. Furthermore, it has been noted that when an auditory stimulus is presented in the presence of background noise (e.g., in a classroom), the correlation between the stimulus and the neural response decreases remarkably in non-musicians, demonstrating the disruptive effect of noise on stimulus detection. In contrast, musicians exhibit significant noise resilience, allowing for a better perception of the target stimulus [48].

This indicates that school-based musical training can improve speech perception, mimicking the benefits observed in professional musicians. The study demonstrated that the benefits of music education are not restricted to private, often expensive lessons that are inaccessible to many; rather, they can be effectively acquired during adolescence and, crucially, during childhood [49]. In fact, a strong correlation appears to exist between the magnitude of brain modifications observed in the colliculus, auditory cortex, and somatosensory cortex, and the age at which the child began learning their musical instrument. Early-stage training significantly enhances the neuroplastic changes that occur in the brain over time (Figure 2). When instrumental or vocal practice is sustained, the corpus callosum becomes denser, reflecting the highly refined development of cognitive and motor pathways. This is accompanied by an expansion of both the cerebrum and cerebellum, as well as areas within the motor cortex.

When listening to or playing music, the body reacts to the rhythm by tapping feet, keeping time, or dancing. Research also shows an increase in the density of Broca's and Wernicke's areas, which are directly associated with language production and processing [40]. Moreover, while genetic predispositions for musical aptitude exist, musical practice acts as the primary trigger that modifies the functional architecture of the standard brain. Evidence shows that merely 15 months of instrumental practice is sufficient to produce notable structural changes in the auditory-motor cortex and the corpus callosum. These neuroanatomical modifications are accompanied by an improvement in motor, rhythmic, and melodic skills. This suggests that music perception is not an isolated, encapsulated process; instead, it shares common motor and cognitive processing sites with other complex functions, most notably language [50].

Musical Training and Cognitive Development

The effects of musical training were evaluated in kindergarten over a 6-month period, with 30-minute sessions per school day focusing on singing, rhythm, listening, coding/decoding, and instrumental practice. Two groups of children with equivalent baseline levels participated in this study: one group received the musical training, while the second served as a control group. The results indicated that by the end of the first grade (CP), students who had undergone musical training the previous year achieved significantly higher scores in French and mathematics compared to their non-trained peers. These enhanced performances were particularly pronounced in memory capacity, which showed substantial development [51]. This cognitive improvement is thought to stem from the creation of numerous neural connections induced by music learning, thereby driving an increase in cerebral plasticity.

Indeed, Schlaug et al. [46] demonstrated an increase in the volume of specific brain structures in musicians, showing that auditory-related brain structures can expand by up to 130% in professional musicians compared to non-musicians. Other cerebral regions also exhibit an increase in size, such as the planum temporal (which includes certain language-related areas), the anterior corpus callosum, and somatosensory regions - the latter developing according to the specific instrument practiced (e.g., the left fingers for a cellist, or the lips for a flutist). This phenomenon was further re-examined using advanced neuroimaging techniques. Right-handed children aged 5 to 6 years, with no prior musical or artistic training and no medical history, underwent brain scans using magnetic resonance imaging (MRI) and diffusion tensor imaging (DTI) - a highly sophisticated technology implemented by neuropsychologist Dr. Pilar Díez-Suárez and her team [52].

MRI and DTI scans were performed both before and after the children completed 9 months of musical training. The neuroimaging revealed the formation of new neural pathways, with reinforced zones facilitating enhanced connectivity between different cortical areas [53]. These findings demonstrate that even a few months of musical training can refine neuronal plasticity, yielding highly beneficial effects on the cognitive performance of young learners.

The Music-Language Correlation

Rhythm consists of a structure characterized by the periodic recurrence of musical events over time. It defines sounds in terms of strong and weak beats, their sequential arrangement, and the accentuation of their intensity. Since the emergence of polyphony, Western musical rhythm has been formalized through its own notation system. This framework standardized rhythms and assigned proportional durations to notes, establishing the metrical rhythm that persists to this day. Furthermore, the correspondence

between music and language would confirm, "Speech is but a sound among all the other sounds that fill our acoustic space" (Table 1). Research conducted by Moon et al. [54] on infants demonstrated that within the first months of life, babies can recognize their native language before they are even able to speak it. This indicates that the fetus perceives external sounds in utero and recognizes the language spoken by the parents. Indeed, a language is characterized by specific acoustic properties, including rhyme, meter, cadence, harmony, inflection, and alliteration (the repetition of initial consonant sounds within closely connected words).

Table 1: Correspondence between music and language properties.

Music		Language	
Composition	- Rhythm-Metric	Construction	- Prosody
	- Harmony		- Syntax
	- Timbre Perception		- Semantics
Unities	Notes	Discreet	Phonemes
Cognitive processes activated by music and language: Perception, Phonological awareness, Memory, Attention, and Information processing speed.			

Certain languages exhibit a distinct singsong quality; for instance, spoken Italian closely resembles music, where syllables punctuate words and impart a rhythmic harmony to sentences. Consequently, rhythm-focused activities are highly relevant in kindergarten, as they prepare children for the syllabic decomposition of words, subsequently facilitating pronunciation and language acquisition [55]. The effects of a combined reading-music training program on the vocabulary and morphosyntactic development of French-speaking second-grade students were investigated in Quebec [56]. The study included 94 children divided into three groups: a control group, a reading-only group subjected to 18 sessions of 55 minutes each, and a third group that participated in identical reading sessions integrated with musical and rhythmic training.

The results showed that all three groups improved their vocabulary through standard schooling, which naturally expands the lexicon across various subjects. Furthermore, both intervention groups (reading-only and reading-with-music) demonstrated significantly greater improvements in vocabulary and morphosyntactic skills compared to the control group. Although no statistically significant difference was observed between the two intervention groups, this outcome does not diminish the impact of music education. Rather, it indicates that rhythmic and musical training is as effective as dedicated reading instruction for lexical growth, likely driven by task diversification, student stimulation, and increased motivation. Actually, "Speech is but a sound among all the other sounds that fill our acoustic space." To highlight the benefits of music on brain plasticity and general learning, researchers studied the impact of musical training on children from disadvantaged backgrounds. Groups of 8-year-old children living in low-income neighbourhoods in Los Angeles underwent a training program that began with a 2-hour weekly introductory phase. After six months, instrumental practice commenced, and the training duration doubled to 4 hours per week.

Cognitive and linguistic assessments were conducted at baseline and annually for two years. A significant improvement in language proficiency was observed only at the end of the second year. This suggests that a single year of musical training may be insufficient to enhance syllable discrimination skills. Achieving this developmental milestone required a two-year commitment, reflecting enhanced auditory processing by the brain and demonstrating that music education must be sustained over at least the medium term to exert its full beneficial effects on language development [57]. Actually, the brain shares some common areas, which are involved in music and language (Figure 4).

Foreign Language Skills

Music represents a structured language defined by its notation, regularities, chords, and nuances. These core characteristics closely parallel the mechanisms involved in foreign language acquisition. Indeed, linguistic prosody encompasses lexical accents, the emotional states conveyed by the speaker, and grammatical structures. Pitch variation is also modulated by the speaker's target audience, shifting notably between adult-directed and infant-directed speech. Consequently, heightened sensitivity to musical nuances appears to facilitate the processing and appreciation of an unfamiliar language. Furthermore, it has been demonstrated that adult musicians whose native language is French are better at detecting prosodic changes located at the end of sentences in an unknown foreign language compared to their non-musician peers [58]. Similarly, after only eight weeks of musical training, children exhibit a significant improvement in pitch processing. These findings indicate that musical education positively impacts students' linguistic capabilities, suggesting that its integration into the school curriculum can enhance foreign language proficiency [59].

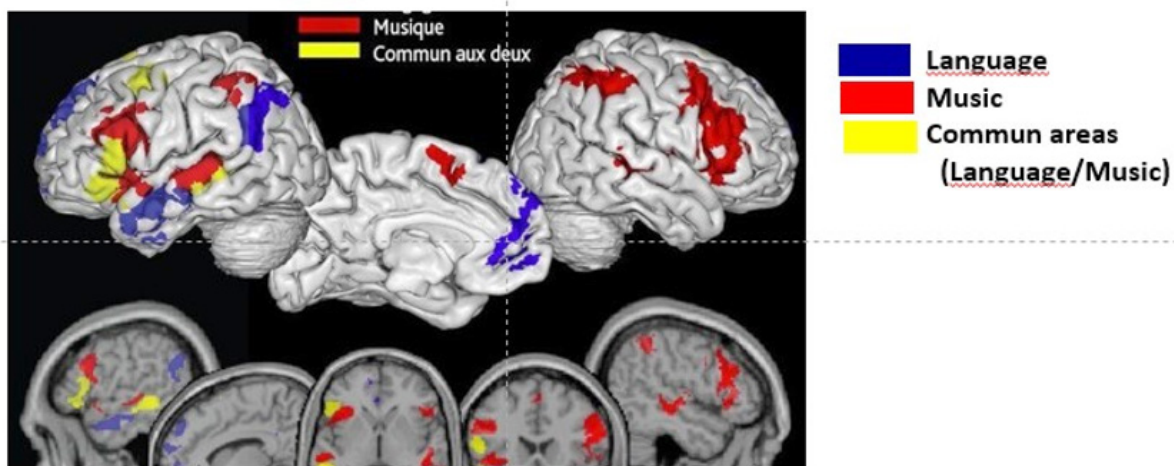


Figure 4: Brain areas interfering in music as well as in language activities.

A recent study underscored the necessity of deeply examining the fusion of music, technology, and language acquisition - a pivotal investigation within the contemporary educational milieu aimed at enhancing language-learning outcomes [60]. English language acquisition has become a global phenomenon, yet millions of individuals worldwide still struggle to achieve proficiency [61]. Despite the wide array of pedagogical techniques available in today's educational landscape, there remains a pressing need for personalized approaches that boost student achievement. In this

context, it has been demonstrated that digital content enriched with multimedia elements - such as text, images, videos, and music - significantly improves learning outcomes. Incontestably, music, which permeates modern life, deeply impacts this learning process [62]. Traditional teaching methods, which often rely on repetitive drills, have been substantially enhanced by technology-based interventions that create more dynamic and interactive language learning environments.

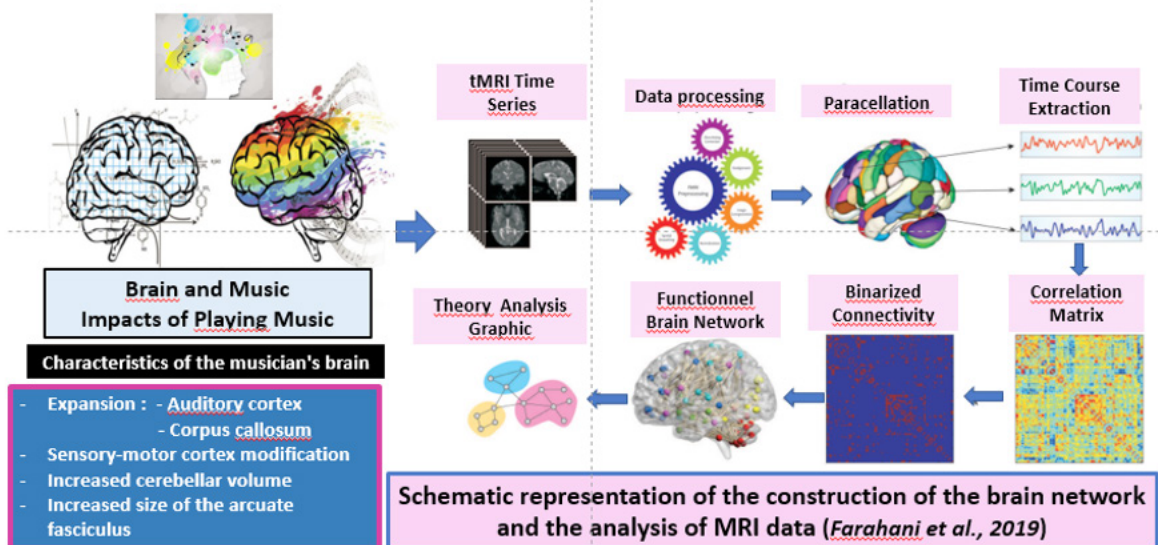


Figure 5: Music et Neurosciences: Musician brain particularities schematized in this brain network construction [65].

Consequently, music - as a universal form of expression that evokes emotion, captures attention, and facilitates memory - strongly promotes language acquisition by providing robust multimodal learning experiences. By simultaneously stimulating different senses and cognitive processes, musical integration taps into learners' natural inclination for rhythm, melody, and song. Ultimately, because academic achievement, creative thinking, and self-esteem are critical criteria for successful language acquisition, integrating musical elements into language instruction enhances outcomes through the synergistic interplay of these factors [63,64]. Following the perception of an auditory stimulus or acoustic vibration, a specific brain network is engaged, with the signal propagation analyzed via fMRI or tractography. First, the neuroimage is reconstructed, and the corresponding data are processed using brain parcellation. This step enables feature extraction and the generation of a correlation matrix, followed by the establishment of a binarized connectivity matrix to map the functional brain network for final analysis. Consequently, the musician's brain was characterized by distinct criteria that evolved according to their musical background (Figure 5).

Impact of Music on Active Listening and Attention

Having established the cognitive potential fostered by musical training, the question arises regarding its specific effects on active listening performance. In infants, evidence shows that newborns recognize their mother's voice and discriminate their native language as early as the 30th week of gestation, which coincides with the functional development of the auditory system; perception at this stage is mediated entirely through prenatal hearing [54]. Interestingly, infants from different countries exhibit distinct babbling patterns that mimic the prosody of their respective native languages. This demonstrates that active listening is actively engaged early on to adapt to the surrounding linguistic environment. Mechanically, music performance demands a high degree of sustained attention across multiple modalities, including score reading, strict tempo adherence, precise finger positioning and movement, breath control (in wind instruments), and synchronization with a conductor's gestures. All these processes require highly demanding attention and active listening to achieve artistic and aesthetic cohesion. Consequently, robust attentional skills are systematically developed through this training. Nevertheless, whether a transfer of these cognitive skills occurs outside the musical domain remains a critical question. To address this issue, professional and non-professional pianists were evaluated using a standardized attention test.

Dyslexia and the Role of Music in Treatment

According to the Larousse Medical Dictionary, dyslexia is defined as "a difficulty in learning to read, characterized by the confusion and reversal of certain letters, persisting beyond normal timeframes" [1]. Expanding on this, Hasbroucq [66] describes it as a persistent and lasting disorder of written language acquisition occurring in children of normal intelligence - as assessed by verbal tests - who receive suitable schooling and do not present any major sensory, emotional, or sociocultural deficits. Similarly, the World

Health Organization (WHO) characterizes dyslexia by a persistent difficulty in learning to read and achieving reading fluency under normal educational and psychological conditions. Standard management typically relies on speech-language therapy and its various remedial methods [66].

Beyond these clinical definitions, the UK Department for Education and Skills (DfES) proposed a broader cognitive approach, defining dyslexia as "a specific difficulty, typically characterised by an unusual balance of skills. Dyslexia affects information processing (receiving, holding, retrieving, and structuring information) and the speed of processing information. It therefore has an impact on skills such as reading, writing, using symbols, and carrying out calculations." This definition reinforces the fact that dyslexia is independent of intelligence. Instead, it primarily affects literacy skills, such as spelling, and is closely tied to language processing. Furthermore, dyslexia frequently co-occurs with other neurodevelopmental conditions, such as dyspraxia, attention deficit disorder (ADD/ADHD), and dysphasia.

More recently, updated consensus data has suggested a refined designation focused on the core nature of the disorder: dyslexia is a specific learning disability in reading at the word level, consisting of difficulties with accurate and/or fluent word recognition and pseudoword decoding. This modern definition focuses exclusively on the primary features of dyslexia, excluding risk factors or potential secondary consequences [68]. Today, dyslexia stands as the most common learning disability. According to the European Dyslexia Association (EDA), epidemiological estimates range from 5% to 15% across European countries, with a higher prevalence in males, affecting approximately three boys for every girl. This difficulty is reflected in the acquisition and automatization of the mechanisms required for mastering written language (reading, writing, and spelling). Biochemically and cognitively, it often manifests as an imbalance between phonological and sequencing pathways, which impairs word comprehension. Ultimately, this disorder disrupts the development of the correspondence between sounds (phonemes) and written symbols (graphemes), leading to the characteristic confusion and reversals of letters and syllables within words (Table 1) [23].

Given the persistent nature of dyslexia and its profound impact on literacy, language processing, and academic achievement, researchers have increasingly explored complementary intervention strategies beyond traditional speech-language therapy. Among these approaches, musical training has emerged as a promising tool for remediation. This perspective is supported by evidence suggesting that music and language share several underlying cognitive and neural mechanisms, particularly those involved in auditory discrimination, temporal processing, rhythm perception, attention, and memory. Consequently, enhancing these core processes through targeted musical activities can improve speech perception, phonological awareness, and reading skills.

Several studies provide empirical support for this hypothesis. Overy [69,70] demonstrated that rhythm- and timing-based musical activities significantly improved phonological processing

and spelling abilities in children with dyslexia. Similarly, Cogo-Moreira et al. [71] reported positive effects of musical training on reading performance, while Weiss et al. [72] found that dyslexic adults with musical experience performed better in pitch discrimination, rhythmic synchronization, and speech-in-noise perception tasks. These findings suggest that musical training can stimulate multiple cognitive functions simultaneously and promote neuroplastic changes that support literacy development. Therefore, music-based interventions could serve as a valuable complement to conventional remediation programs, particularly for individuals who exhibit persistent reading difficulties despite traditional therapeutic approaches. Moreover, research in the field of neuroscience used machine-learning methods to achieve deeper insight into the neurobiological foundations of dyslexia [23].

Within this interdisciplinary framework, AI-integrated music technologies offer a promising therapeutic and pedagogical avenue for addressing dyslexia. AI-driven systems precisely analyse rhythmic perception, auditory discrimination, and sensorimotor synchronization to design individualized interventions tailored to specific cognitive profiles. Utilizing machine learning algorithms and adaptive platforms, these systems dynamically adjust musical training in real time to target phonological awareness, working memory, and temporal processing skills. Furthermore, intelligent tutoring systems enhance engagement by transforming repetitive phonological exercises into interactive musical tasks, thereby mitigating cognitive load and learning anxiety [23]. This convergence of music therapy and AI personalization enables continuous performance monitoring and data-driven feedback, empowering educators to refine intervention strategies. Ultimately, AI-supported music transitions from a complementary resource into an adaptive cognitive training medium that robustly improves literacy-related skills and fosters inclusive educational environments.

Conclusion

This brief synthesis highlights the human brain as a fascinating, highly dynamic, and organized organ that continuously adapts to environmental activities and demands. Engaging in music yields significant cognitive and perceptual benefits that extend beyond the musical domain. Specifically, children who learn a musical instrument exhibit enhanced speech prosody representation, a richer vocabulary, superior reading skills, and greater learning agility. Additionally, musical training facilitates speech perception in noisy environments, improves the discrimination of diverse sound sources, and strengthens attentional control.

These findings strongly suggest that the educational sector should place greater emphasis on music education. This discipline deserves promotion because it generates millions of new neural connections and reinforces existing networks. Furthermore, language and music are deeply intertwined; their cerebral processing is remarkably similar, if not nearly identical, sharing the same neural pathways. A musician's auditory precision and extensive neural development lead to enhanced verbal processing and a stronger linguistic representation. Consequently, it is

crucial to evaluate current school-based musical activities and their potential to foster this language-music synergy. Could these linguistic benefits be systematically leveraged for all children within a standard classroom? What role should educators play in this integration, and what specific prerequisites do they need to successfully fulfil this mission?

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Conflict of Interest

No conflict of interest.

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