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**Review Article**

# Music, Language, and Autism: Neurological Insights for Enhanced Learning

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## Abstract

This comprehensive review thoroughly explores the intricate relationship between music and language, encompassing their historical, cognitive, and neural dimensions. It draws evidence from ancient Chinese civilizations dating back to 4500 BC to analyze the coexistence and parallel evolution of music and language for the first time. Comparative studies illuminate the shared and distinctive aspects of pitch, rhythm, and syntax inherent to music and language. The examination extends to the diverse impact of music, including second language acquisition, phonological awareness, pitch processing, memory, and cognitive skills. This influence is also observed among individuals with Autism Spectrum Disorder. The paper further examines the intricate neural connections, neural overlapping, networks, structural processing, bidirectional relationships, cross-modal transfer effects, and brain plasticity that underpin music and language. It reviews music interventions for enhancing language and cognitive abilities, particularly in the context of autism spectrum disorders. However, the precise role of music and its intricate neural mechanisms in shaping language-related outcomes within Autism spectrum disorder groups remains incompletely understood. Further interdisciplinary research integrating disciplines like neuroscience, psychology, sociology, and related fields is imperative to deepen our comprehension and unlock the precise neural mechanisms and interventions that can foster enhanced language and cognitive development in individuals with autism.

***Keywords:*** ***Music-language connections, autism, music therapy and interventions, language development, neural mechanisms.***

## Introduction

Music is universally recognized as a fundamental aspect of human cognition, transcending cultural barriers as people from diverse backgrounds can understand and appreciate it without need for translation. Music perception involves the processing of pitch, rhythm, and timbre, activating different brain regions during various stages. Notably, musical training has been found to induce neuroplastic changes in the brain, fostering enhanced connectivity between brain regions involved in music processing and other cognitive domains. Brain regions such as the superior temporal gyrus and the inferior frontal areas have consistently been identified as crucial for music processing. The initial processing of sound occurs in small sensory areas of the superior temporal cortex, transmitting information to higher-level areas responsible for handling more complex aspects of music, such as the aforementioned pitch, rhythm, and timbre.

The complex relationship between music and language has captured the attention of researchers, prompting investigations into the brain structures involved in processing these two cognitive domains. How do the processing mechanisms for music and language differ, and how do they relate? Research on their relationship has revealed fascinating connections and highlighted the potential benefits of integrating music into language learning. Moreover, unraveling the influence of language and music acquisition on brain structuring could yield valuable insights into the nuanced evolution of the human brain. This inquiry also offers the prospect of illuminating the effectiveness of music therapy as a facilitator of language attainment, particularly among individuals with neurodevelopmental conditions like autism.

Autism spectrum disorder (ASD) is a neurodevelopmental condition characterized by social communication and interaction difficulties and the presence of restricted and repetitive patterns of behavior, interests, and activities, and sensory processing anomalies causing functional impairment in social, educational, and occupational domains [1]. According to the latest report from the CDC's "Autism and Developmental Disabilities Monitoring Network" [2], the prevalence of autism in children has risen to 1 in 36. This marks a significant increase when compared to the previously estimated figures of 1 in 110 in 2016 and 1 in 44 in 2021. Notably, this report does not include information regarding diagnosis during the COVID-19 pandemic. In the unprecedented disruption and social isolation caused by the COVID-19 pandemic, children with ASD faced a heightened vulnerability to the adverse effects of the crisis [3]. Simultaneously, the economic ramifications of autism in the U.S. have been significant. In 2020, the annual cost linked to autism was approximated at $268 billion, with projections foreseeing a further escalation to an estimated $461 billion by 2025[4].

Approximately 20% to 30% of autistic children develop epilepsy and between 40% and 80% have an intellectual disability [5,6]. Autistic children might have difficulty learning language. Some may have a history of language disorder or delay, encompassing delays in single-word or phrase speech, and some children might regress, losing previously acquired language skills [7]. Studies indicate that language development in autism typically follows a qualitatively similar but delayed pattern compared to typically developing children. Language and speech profiles in individuals with ASD can vary widely. Language impairments in autism often involve difficulties in social use of language and the quality of spoken communication. Therefore, implementing language interventions like regular speech therapy in autistic children can pose significant challenges.

Music therapy and context-based interventions show promise in supporting language development in individuals with autism. The clinical utilization of music to facilitate the developmental and therapeutic processes in autism has a long history. Traditionally, music therapy for ASD has centered on social interaction, communication skills, and social-emotional behaviors. Recent research found the positive impact of music on the language and cognitive development of individuals with autism, suggesting that music-based developmental training could acquire a crucial functional role in autism treatment. The proposition presents fresh research avenues for therapists and researchers to reevaluate the role of music as an intervention, expanding the current clinical landscape of music therapy for autism to support healthy neurodevelopment in ASD individuals.

This review aims to examine the connections and underlying interaction mechanisms between music and language. It also explores the potential of music intervention for enhancing language and cognitive development within the ASD group, with the primary objective of providing fundamental information for developing new alternative support options for autistic children.

## 1.The connections between music and language

### 1.1 The historical roots of music and language-the co-evolution of music and language in ancient times.

Music and language are two complex systems that hold fundamental roles in human communication, yet the origins and evolution of both remain subject to ongoing debate and exploration. Researchers have questioned whether music preceded language as an early form of communication or if it emerged as a byproduct of the cognitive abilities developed to support language. The following is just one example of the correlation (**Figure 1**).

In 1953, archaeologists discovered the Banpo site [8], an ancient village dating back to approximately 4500-3750 BC, situated around 6 kilometers northeast of the city of Xi'an in present-day Shaanxi, China. They found various tools and utensils including pottery, stone tools, bone artifacts, grinding slabs, and querns, providing evidence of the village's agricultural and handicraft developments as well as a glimpse into the lives of its ancient inhabitants.

One artifact discovered at Banpo was an ancient musical instrument called the 'Xun'. The Xun is a hollow, egg-shaped vessel played by blowing air into the mouthpiece while covering the holes with fingers in order to produce different sounds. At the Banpo site, there are two of these instruments discovered, one with only one hole, the other with two, with the latter being capable of playing a minor third interval (i.e. 'G' and 'B-flat'). It is speculated that the Xun was likely used during social and religious events, such as rituals, ceremonies, and gatherings [8].

In that same location, archaeologists unearthed 27 distinct symbols depicted on pottery and pottery fragments. Strikingly, these symbols bear a strong resemblance to an early form of the Chinese script, leading researchers to speculate that they could potentially be precursors to written language. These written forms of communication ran parallel to the occurrence of the Xun during the same period [8].

The archaeological findings reveal that the ancient instrument known as the Xun underwent an evolutionary transformation, progressing from a simple style to more intricate variations. Comparable vessel flutes to the Xun have been uncovered in tombs dating back to the Xia dynasty (around 2070-1600 BC). These instruments were equipped with three finger holes and had the capacity to produce the notes do, mi, so, la, and fa. The shape of the instrument and the number of finger holes of the Xun as we know it today were standardized during the Shang dynasty (1600-1046 BC). During this era, most Xun instruments were designed with five-finger holes, allowing them to produce all the tones and half-tones in a single octave. By the Zhou dynasty 1046-256 BC), it was a common instrument and was played in the imperial courts. During the Spring and Autumn Period (770-460 BC), the Xun already had six sound holes, capable of producing complete pentatonic and heptatonic scales. The evolution of this unique ancient instrument serves as an invaluable case study illustrating the early development of music and musical instruments within ancient civilizations [9].

Similarly, Chinese characters have undergone a remarkable evolution. They originated from the Oracle Bone Script style, which emerged on oracle and animal bones during the late Shang Dynasty (1250-1200 BC). This progression led to Jinwen, writing cast or engraved onto bronze artifacts. Jinwen originated during the middle period of the Shang Dynasty (1300 BC to 1046 BC) and thrived throughout the Zhou Dynasty (1046 BC-220 BC). Following Jinwen, Xiaozhuan Script marked the zenith of characters in ancient writing. It was developed into the script for standardizing writing systems by Qin Shihuan (221 BC). Subsequently, Xiaozhuan's prominence paved the way for the Li script (307-217 BC) and the Kai script (202 BC-618 AD), both of which resembled modern Chinese typography [10].

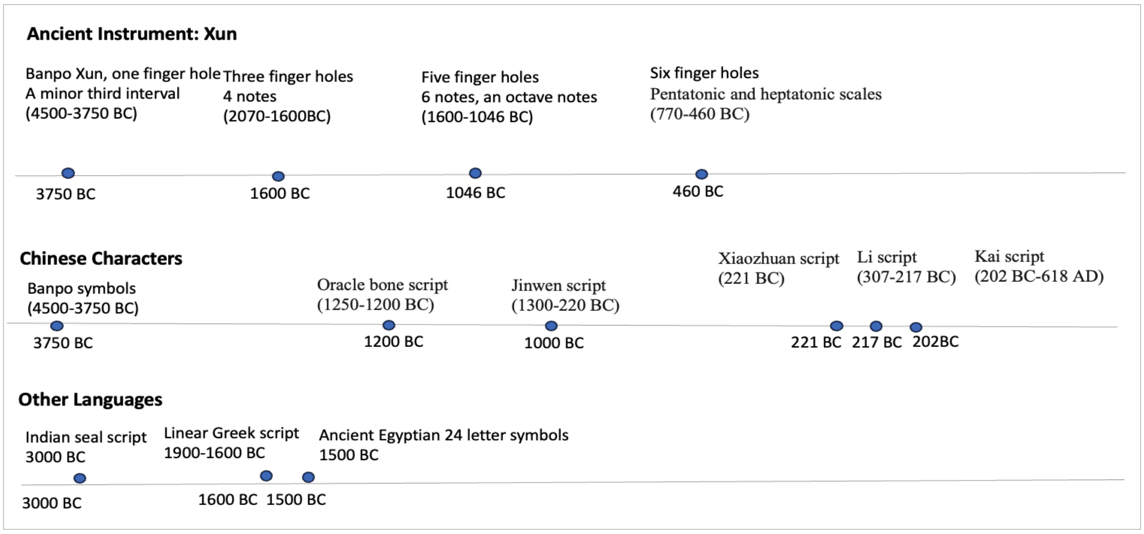


**Figure 1: The evolution of the Xun instrument and Chinese characters.**
The timeline is not drawn to scale; rather, it is designed to represent the chronological sequence.

Figure 1 illustrates a timeline depicting the evolutionary journey of the Xun and Chinese Characters. Although the spoken language remains beyond our examination, it is reasonable to recognize that both music and language emerged early as fundamental channels of expression and communication. Gradually, these forms evolved from their rudimentary beginnings into increasingly sophisticated structures. While the precise interplay between the two domains continues to be under investigation, it's clear that both language and music have been integral to human history, culture, and communication, ultimately enhancing the human experience. From an evolutionary perspective, the notion of music and language sharing common origins holds significant merit [11].

### 1.2 The benefits of music for language and cognitive domains

Plenty of research has been conducted that demonstrates the thought-provoking connections between music and language. For example, musical training can have a positive impact on various linguistic skills, including second language acquisition, phonological awareness, pitch discrimination, verbal fluency, memory, and reading.

#### 1.2.1 Music enhances second language acquisition

Individuals with musical talents often exhibit a heightened aptitude for learning foreign languages. The findings show a significant correlation between higher musical aptitude, better second language pronunciation skills, the ability to discriminate chords accurately, and greater brain activation in response to musical stimuli. Moreover, regular musical practice may also modulate the brain's linguistic organization and alter hemispheric functions in individuals who have engaged in music training for an extended period [12]. Musical training can influence the processing of acoustic stimuli in both speech and non-speech contexts. Musicians process unvoiced stimuli in a distinct manner compared to non-musicians and proposed that musicians employ the same neural networks for analyzing unvoiced stimuli as they do for voiced stimuli [13].

#### 1.2.2 Phonological awareness and reading

Musical training can have a positive impact on phonological awareness, especially for larger phonological units like syllables and words, which is crucial for reading and writing skills [14,15]. Even children with developmental dyslexia can benefit from music training. Flaugnacco [16] and Skubic [17] suggest that phonological awareness is linked to well-developed hearing abilities. Engaging in musical activities that demand strong listening skills, such as sound and environment orientation, can aid in developing phonological awareness.

Phonological awareness is a vital skill linked to reading. Research examining the impact of music on reading comprehension yields varied outcomes. While certain studies demonstrate positive effects, others indicate no significant influence. These diverse findings suggest that the connection between music and reading comprehension hinges on multiple factors, including music type, context, and individual disparities. Sofologi's study [18] probed the impact of music on reading comprehension and found that children with instrumental music training registered higher performances in reading comprehension tests. Meta-analyses investigating the correlation between musical training and phonological awareness, however, don't consistently uncover evidence of improvements in reading-associated skills [19,20]. An examination by Aksoy et al.[21] scrutinized 31 meta-analysis studies published between 2010 and 2021. Among these, 10 studies demonstrated negative effects, while 21 showed positive impacts. The broad spectrum of methodologies and participant characteristics within the meta-analysis makes it challenging to draw conclusive findings about the influence of music education on reading-related skills.

#### 1.2.3 Pitch processing

Musical training shows potential for benefiting second language learning and other linguistic tasks by enhancing pitch processing skills, leading to improved speech perception and production. Musical pitch can lead to better pitch perception for language-related tasks [22]. They found that training with musical pitch can lead to better pitch perception for language-related tasks. This was observed in both musicians and non-musicians, including adults and children. Even a short exposure to musical pitch processing influenced how individuals perceived and processed pitch in language. Musical expertise not only improved pitch processing in music but also in speech. This transfer of skills between music and language could have useful applications for second language learning. The researchers also studied dyslexic children and found that they had difficulty discriminating against strong pitch changes, unlike normal readers. Jäncke [23] suggests that musical training can enhance the neural processing of speech melody, even in individuals who are not tone language speakers. Speech melody refers to the pitch variations and patterns in speech that contribute to the expressive and meaningful aspects of language.

#### 1.2.4 Verbal fluency and memory

The study found that music positively affected verbal fluency, with participants showing improved performance on verbal fluency tasks after listening to music [24]. This suggests that music may potentially enhance language-related cognitive functions, such as verbal fluency. However, it is important to note that other studies have found no strong influence of background music on verbal learning [25].

#### 1.2.5 The effect of music training on various cognitive domains

Musical training enhances the brain's executive control network for auditory processing beyond music, particularly in terms of sustaining attention with minimal variability. The study of Strait [26] suggests that musical training shapes auditory function by promoting the extensive recruitment of additional sensory mechanisms related to cognitive control, such as working memory and attention. However, the specific neurobiological processes involved require further investigation.

Milovanov et al.[12] and Miendlarzewska et al.[27] discuss the potential benefits of musical training that extend beyond linguistic abilities, such as improving working memory, mathematical skills, and spatial abilities. Miendlarzewska highlights how musical training can positively impact cognitive processes, including motor coordination, temporal processing, and synchronization. They emphasize musical training can shape neural networks and enhance connectivity in regions involved in auditory processing, motor coordination, and cognitive control. The studies provide valuable insights into the multifaceted effects of musical training on cognitive development, underscoring the significance of rhythm, reward, and other modulating variables. It suggests music's potential as a tool to promote cognitive abilities and emphasizes the need for further research in this area.

Ettlinger et al.[28] review the role of implicitly acquired knowledge, implicit memory, and their associated neural mechanisms that link implicit memory, language, and music. One key finding is the significant overlap of brain structures involved in implicit memory, the acquisition of linguistic or musical grammar. This convergence suggests a potential common learning mechanism shared by both music and language.

### 1.3 A comparative approach to understanding music and language

Both music and language involve the activation of similar neural mechanisms, particularly in the areas of the brain involved in auditory processing and memory.

Throughout history, music and language have played significant roles as modes of expression and communication. As time passed, both underwent evolution, transforming from simple styles into more intricate and sophisticated systems. Language, in particular, has developed into a highly complex means of conveying thoughts, sharing information, and fostering social connections among individuals. Simultaneously, musical systems and instruments have grown more elaborate, developing ever-evolving harmonies, rhythmic elements, and techniques. Despite sharing the common elements of sound as a form of communication, music and language maintain distinct characteristics, serving unique purposes and operating within separate cognitive and emotional domains. Language is primarily used to convey explicit meaning, whereas music is often used for expressing complex emotions, evoking imagination, and communicating abstract experiences that transcend the boundaries of explicit language. This distinction highlights the diverse and multifaceted nature of music and language as essential aspects of human culture and communication. Studying the similarity between music and language can aid in our comprehension of the nature of the two and their shared underlying mechanisms in terms of the cognitive processes and neural mechanisms associated with them.

**1.3.1 Structural similarity: syntax**

Music and language share structural and evolutionary commonalities. Both consist of sounds and make use of rhythm, pitch, volume, stress and pause [29]. Koelsch [30] provides a comprehensive overview of the neural basis of music perception, including the processing of musical syntax and its relation to linguistic syntax. The paper suggests that musical syntax shares some similarities with linguistic syntax, such as the use of hierarchical structures and the processing of syntactic dependencies. However, the paper also notes that there are important differences between musical and linguistic syntax, such as the lack of propositional semantics in music. Temperley [20] underscores the connections between cognitive processes in music and linguistic syntax, indicating overlaps in neural processing and hierarchical structure building. Both music and language involve hierarchical structure building-the combination of smaller units into larger units in a hierarchical fashion, activating similar neural mechanisms, particularly in the areas of the brain involved in auditory processing and working memory. The paper proposes a more abstract level of comparison, called "syntactic architecture," which is needed between music and language syntax.

**1.3.2 Synchronizing linguistic stress and musical meter**

Musical meter refers to the rhythmic organization of beats and accents in music. It involves the grouping of beats into regular patterns, such as doublets or triplets. Linguistic stress refers to the emphasis placed on certain syllables or words within a sentence. Stress can affect the meaning and interpretation of a sentence or phrase.

There may be shared rhythmic patterns between music and language across cultures [20,30]. Processing rhythmic patterns and stress in one of the domains can influence the processing of similar patterns in another. Patel and Daniele [31] studied rhythmic patterns in both the English and French languages as well as in classical music. They found significant differences between English and French musical themes, which also reflect the differences in the rhythm patterns of spoken English and French, and suggested that people speak influences the rhythm patterns of their culture's music. Franich [32] explored the rhythmic mapping between language and music in African tonal languages, highlighting the importance of stress in determining rhythmic alignment in text setting. Hannon [33] suggested the rhythmic differences between stress- and syllable-timed languages have parallels in children's songs. Gordon et al.[34] examined the interplay between music and language processing through EEG (electroencephalogram) patterns associated with song prosody. Their research found that the placement of linguistic stress within a sentence could align with rhythmic patterns and metrical structure in music, with the stressed syllables aligning with the accented beats. Clayton [35] explores the connection between linguistic prosody and musical meter in songs, investigating how they work together to enhance musical beat tracking and lyric comprehension. The study suggests that aligning linguistic stress and musical meter in songs synchronizes neural activity with strong syllables, leading to improved learning and recall of song lyrics. This alignment of stressed syllables with strong beats in music helps direct the listener's attention, making it easier to segment syllables and comprehend the song's lyrics. The paper emphasizes the structural similarities between syllabic stress and musical meter, highlighting their shared multileveled patterns of accentuation.

The findings present the interplay between linguistic and musical elements in songs, shedding light on how they collaboratively contribute to the overall listening experience and cognitive processes involved in understanding song lyrics, indicating that synchronized neural oscillations in the brain, achieved through the alignment of linguistic stress and musical meter, contributes to improved musical beat tracking and lyric comprehension.

**1.3.3 Differences between music and language**

Despite some similarities between music and language, such as the use of syntax and the involvement of neural processing, it is essential to recognize the fundamental differences between the two. These differences indicate that music and language pertain to distinct cognitive domains. Music and language differ in their functions in terms of communication. Language is commonly used to express propositional meaning, whereas music can only convey more subtle meaning such as emotion or affect [36]. Additionally, they also differ structurally beyond the surface level in terms of pitch, rhythm, and syntax. The fundamental differences between music and language, including differences in semantic content, syntax, production and reception, and evolutionary origins were discussed by Temperley [20], which include:

*Semantic content:* Language has propositional semantics, conveying specific meanings through words and grammar. Conversely, music does not have propositional semantics, and its meaning is thus more abstract and subjective.

*Syntax:* Music and language have syntax, but the two domains use distinct structural elements. Musical syntax is built on patterns of repetition and variation, while linguistic syntax uses words and follows grammatical rules. Linguistic syntax is closely linked to conveying specific ideas, while musical syntax does not possess direct propositional meaning as it lacks propositional semantics. Musical syntax demonstrates greater flexibility compared to that language. This suggests that music and language serve different purposes in communication. To understand the relationship between music and language, a broader exploration of syntax, including the "syntactic architecture" of linguistic and musical systems, is necessary.

*Production and reception:* Language is primarily used as a tool for communication, and its production and reception are closely linked to its communicative function. On the other hand, music can be produced and received for various reasons, including emotional expression, entertainment, and aesthetic enjoyment.

*Evolutionary origins:* Language is thought to have evolved as a tool for communication and social interaction, while the evolutionary origins of music are less clear. Music may have evolved as a tool for emotional expression or as a byproduct of other cognitive abilities.

## 2. Uncovering the neural mechanisms involved with music and language

The relationship between music and language functions is a topic of interest in the field of neuroscience. Advances in brain imaging technology have challenged the idea that language and music involve two distinct brain mechanisms, as it is becoming clear that there is a whole lot of overlap between the two. Jäncke [23] discusses the relationship between music and language, drawing on evidence from neuroscience, psychology, sociology, and other fields. Both music and language processing share neural mechanisms, including the involvement of the left hemisphere of the brain. Both domains also share cognitive resources for structural processing, suggesting that there may be shared underlying mechanisms between the two domains.

### 2.1 Neural overlap mechanisms

Over the past decade, there has been a linear increase in research studying the neural overlap of music and language processing. The majority of studies have used one of the four following approaches to map associations, overlaps, or similarities between musicality and language: (a) musical training or intervention studies [25], (b) comparisons between musicians and non-musicians on language-related tasks [37], (c) comparisons of neurocognitive processing of linguistic and musical information [38], and (d) using EEG [39] and neuroimaging techniques [40] such as fMRI [41] to compare the brain activation patterns during musical and linguistic tasks. Several studies have explored the relationship between musical aptitude and non-native speech-sound processing, and suggest that music and language skills are interconnected. Musical training can fine-tune the brain's executive control network for auditory processing, which can yield positive effects on other cognitive domains, including language processing and the development of neural mechanisms related to language. Music can interfere with the processing of syntactic structures by disrupting the neural mechanisms involved in syntactic processing, and the neural and psychological resources of music and language processing strongly overlap [42]. The presence of neural overlap in processing music and speech does not necessarily imply the sharing of neural circuitries, but the possibility of neural separability between music and speech occurring in overlapping brain regions [40].

Patel proposed that the components of language and music may be compounded into large meaningful units in a structural hierarchical manner-grammar and harmony or rhythm. The OPERA framework, proposed by Patel [43], is an important work to help understand why musical training can enhance speech processing. This hypothesis suggests that a shared population of neurons in the musicality and language brain networks plays a role in underlying pitch processing. The findings of Shahin [44] align with the OPERA framework, indicating a neurophysiological link between musical training and speech perception. They propose that skills acquired through musical training may transfer to and improve speech perception. The paper further emphasized that the neural encoding of speech is influenced more by inherent auditory skills rather than formal music training. Patel [45] proposed the expanded OPERA hypothesis incorporating the idea of shared cognitive processing into the discussion of neural overlap, based on the proposals that musical training enhances auditory attention and working memory.

Jantzen [46] explores the overlap of cognitive and neural processes involved in musical and language-related tasks. The paper sheds light on the overlap in cognitive and neural mechanisms utilized during activities in these domains, revealing functional relationships between musicality and language within cognitive and neural frameworks. It highlights the potential for cross-modal processing and influence between the two domains. Additionally, the paper underscores the significance of comprehending the functional relationships between musicality and language within cognitive and neural contexts.

The brain overlap region for music and language processing includes the left hemisphere's auditory cortex, specific cortical regions [47], the mirror-neuron system [48], Broca’s area (occupying the left IFG) [40] and right hemisphere areas [49]. Jantzen investigates whether musicians engage right hemisphere areas traditionally associated with music for the processing of speech sounds. The study found greater activation of the right middle temporal gyrus and superior temporal gyrus in musicians, suggesting the recruitment of right hemisphere regions for discriminating speech sounds. The findings indicate that musical training enhances the processing of acoustic information for speech sounds and broadens the language network in musicians.

### 2.2 Exploring the neural networks

Research in cognitive neuroscience has been guided by the assumption that brain regions are specialized for a function. However, research on tonal encoding of pitch has discovered that more than one brain region contributes to pitch's musical interpretation, which is likely to recruit a vast network. The evidence points towards the connectivity between the right auditory cortex and inferior frontal gyrus (IFG) as being necessary for the normal development of musical abilities [48]. Recent network analyses have revealed highly connected network “hubs” [51], which may well be shared by music and speech processing. Hubs support efficient control or integration by facilitating the convergence of neuronal signals from different sensory modalities (e.g. auditory and motor) or cognitive domains (e.g. musicality and language).

Peretz [40] proposed that neural overlap does not necessarily entail neural sharing. The neural circuits established for musicality may be intermingled or adjacent to those used for a similar function in language and yet be neurally separable. fMRI combined with multivariate decoding methods, fMRI adaptation paradigm [52] was used to investigate the shared neural circuitry. The standard use of fMRI attempts to identify the neuronal regions that respond to music and speech processing. However, it is limited in its ability to determine the specific neuronal populations or neighboring groups of neurons involved in both music and speech processing [53]. Neuroimaging techniques, when paired with multivariate pattern analysis methods from machine learning algorithms, exhibit sensitivity in identifying activity patterns linked to specific stimuli, tasks, or mental states. This capability extends to recognizing neural segregation in overlapping regions [54]. Sammler et al. [55] used fMRI adaptation paradigm technique to induce neural adaptation to listening to lyrics, melodies, and songs. The result showed that the left mid-STS showed an interaction of the adaptation effects for lyrics and tunes, suggesting shared processing of the two components.

Both music and language involve complex and multifaceted processing mechanisms. This complexity makes it difficult to identify the specific neural mechanisms involved in each domain and to determine how they interact. There are methodological challenges in studying the neural sharing between music and speech, including the choice of experimental tasks, the use of appropriate control conditions, and the selection of appropriate neuroimaging techniques. Interdisciplinary techniques are necessary to determine the specific neural mechanisms involved in each domain.

### 2.3 Structural processing

The relationship between structural processing in music and language has received increasing interest in recent years. Fedorenko [56] investigates whether language and music share cognitive resources for structural processing. The study used sung materials and manipulated linguistic complexity and musical complexity to investigate the overlap in structural processing between language and music. The findings suggest that language and music share cognitive resources for structural processing, with separable syntactic representations but shared cognitive resources to integrate these representations into evolving structures. The Shared Syntactic Integration Resource Hypothesis (SSIRH) proposes that music and language rely on separable syntactic representations but recruit shared cognitive resources to integrate these representations into evolving structures.

### 2.4 Bidirectional relationships

There is a bidirectional relationship between music and language with potential for cross-domain transfer effects, meaning that language and music can influence each other. Asaridou [57] explores the shared domain-general mechanisms between speech and music in shaping the development of the listening brain. Shared auditory skills accounts suggest that bidirectional influences are inherent in the relationship between music and language since they attribute the influence of both to the same auditory skills. They also suggest that these influences can occur at multiple levels, from sounds and melodies to semantics and syntax.

Bidelman et al.[58], using a cross-sectional design, compared the performance of musicians to that of tone-language (Cantonese) speakers on tasks of auditory pitch acuity, music perception, and general cognitive ability (e.g., fluid intelligence, working memory). They found that tone language speakers and musicians share enhanced perceptual and cognitive abilities for musical pitch and suggest that there are shared underlying mechanisms between the processing of language and music in the brain.

Calma-Roddin [59] explores the interference patterns observed in the N400 event-related potential (ERP) component across the domains of language and music. They measured these patterns using electroencephalography (EEG) or magnetoencephalography (MEG). They found interaction effects between language and music processing. These findings suggest that language and music may share processing resources involved in the computation and maintenance of the abstract hierarchical structure.

### 2.5 The potential for cross-modal processing between music and language

The concept of cross-modal processing has been extensively studied in sensory perception. Researchers have explored how different sensory modalities, such as vision, hearing, touch, taste, and smell, interact and influence each other's processing. For example, studies have shown that visual information can influence the perception of auditory stimuli, and vice versa. This cross-modal interaction can occur at various levels of sensory processing, from early sensory areas to higher-order cortical regions. Music and language are both used for communication and expression to convey emotions and affective content. Music and language can influence each other in terms of perception and cognition. For example, musical training can enhance language processing skills, and exposure to language can affect musical perception.

Jäncke [23] proposed that there is potential for cross-domain transfer effects between music and language processing. The transfer effects may be due to shared neural mechanisms and cognitive resources between music and language processing. The transfer effects may be more pronounced for near-transfer skills, such as phonological awareness, than for far-transfer skills, such as reading comprehension. The transfer effects between music and language processing may be bidirectional, with potential for cross-domain transfer effects.

The connection between linguistic stress and musical meter highlights the potential for cross-modal processing between music and language. Cross-modal processing [60] refers to the interaction and integration of information from different sensory modalities. It involves the ability of the brain to combine and process signals arriving from multiple senses simultaneously. This interaction allows information from one modality to influence the processing of information in another modality, leading to a holistic and integrated perceptual experience.

### 2.6 Brain plasticity

The brain exhibits plasticity in response to musical training, and this can have positive effects on other cognitive domains, including language. Sociocultural factors, such as musical training and language experience, can influence the relationship between music and language processing.

Brain plasticity, also known as neuroplasticity, refers to the brain's ability to reorganize itself by forming new neural connections and modifying existing ones throughout life. Learning and new experiences can lead to the strengthening of neural pathways, while infrequently used pathways may weaken and eventually be pruned [61]. Brain plasticity involves changes in the physical structure of the brain, such as reshaping individual neurons and altering the connections between them. Plasticity can occur in response to intrinsic or extrinsic stimuli, allowing the nervous system to reorganize its structure, functions, or connections [62]. Plasticity is more pronounced in the developing brain, but research has shown that the adult brain can also undergo significant changes. Jäncke mentioned that musical training possesses the capacity to reshape brain structure through plasticity, yielding beneficial effects on various cognitive domains, including language [23].

Moreno and Bidelman also demonstrated how various cognitive functions are affected by musical activities and proposed that highly trained musicians may exhibit enhanced brain plasticity in the networks associated with these functions [63]. The study offers valuable insights into the neural and cognitive effects of musical training, emphasizing the positive effects of music on brain plasticity and cognitive abilities. Wang provides an overview of the neurobiology of music [64]. They discuss how various brain regions collaborate during music performance or listening, forming a hierarchically structured sequence of complex activities. The paper suggests that hemispheric specialization for musical processing may develop with age. Numerous studies have demonstrated differences in gray matter between musicians and non-musicians in different brain areas. Playing a musical instrument involves procedural and motor learning, leading to plastic reorganization in the human brain. These changes include the unmasking of existing connections and the formation of new ones. Both functional and structural brain changes occur in instrumentalists as they adapt to the demands of their practice. The paper also highlights the shared syntactic-like structure used by language, action, and music. It suggests that there is a complex and multifaceted connection between music and language processing, involving the presence of shared neural mechanisms and the potential for plasticity and cognitive benefits. However, there are also differences in the brain regions activated during music and language processing, highlighting the unique nature of the two domains.

Moderating variables of music training-induced neuroplasticity are reviewed by Merrett [65]. These include age at the commencement of training, sex, absolute pitch, type of training, and instrument of training. These moderating variables can affect the degree and nature of plastic changes in the brain.

## 3. The effect of music training on various cognitive domains of individuals with ASD

### 3.1 Music's effects on various aspects of individuals with ASD (Table 1).

#### 3.1.1 Language acquisition

Jones [66] investigated the effect of music therapy on language acquisition in children with ASD aged 3-8 years. The study found that music therapy led to an increase in word utterance, progress toward special education goals, emotional well-being, and expressive communication in the home and community.

#### 3.1.2 Pitch processing

Superior pitch processing has been observed in individuals with ASD through the studies of behavioral and brain imaging on auditory-musical processing in ASD [67]. Chen used meta-analysis to analyze the role of pitch in auditory perception of music and language in individuals with ASD and found enhanced pitch processing abilities in this population [68]. Rimmer found a positive correlation between musical beat perception and phonological awareness skills in children on the autism spectrum [69].

### 3.1.3 Verbal fluency

There is limited research on the direct effects of music on verbal fluency in autism, the available research suggests that music can have positive effects on language acquisition and communication skills in individuals with autism. These findings highlight the potential of music therapy and music-based interventions to support verbal fluency in this population.

### 3.1.4 Working Memory

Research on the direct effects of music on working memory in autism, is also limited. But the available research suggests that music can positively affect brain connectivity, cognitive function and working memory [70].

### 3.1.5 Cognitive Domains

Participation in musical activities yields favorable outcomes for cognitive advancement in autistic individuals. These activities improve auditory processing [67], working memory, and attention [70].

### 3.1.6 Social proficiency, emotional regulation, communication and sensory

Music offers a powerful means of communication, nonverbal expression and interaction, social proficiency, and emotional regulation for individuals with autism. For children with autism, music serves as a potent means for children with autism to express themselves non-verbally. It can be a powerful tool for communication and self-expression [71]. It can enhance neurodevelopment in those diagnosed with autism, aiding sensory assimilation [72].

### 3.1.7 Motor

Srinivasan [73] reviews the effectiveness of "music and movement" therapies for children with ASD and highlights the multisystem impairments of ASDs, including motor, cognitive, and social deficits, and explains why music and movement therapies are a powerful clinical tool for addressing these impairments [70].

### 3.2 Neural mechanism of music on ASD

Early research suggested that the processing of music may be preserved in autism even when language abilities are impaired [74]. Janzen [70] discovered that engaging in musical activities activates a network of brain regions related to hearing, movement, emotion, pleasure, and memory. He proposes that music can facilitate the transfer of therapeutic effects to non-musical domains through structural and functional brain changes. Interestingly, evidence points out that individuals with ASD challenges with auditory imagery preserved or superior music-processing skills compared to their typically developing peers, despite having challenges with auditory imagery. This observation underscores a separability between auditory imagery and control of musical memories in the ASD group [75].

Research findings show that music is a unique domain for people with ASD to assess perception, reward, emotion, and associated physiological reactions and neural circuitry. Musical abilities found to be strengths among individuals with ASD encompass musical pitch perception, musical memory, and the identification of music-evoked emotions. These strengths also extend to adults with ASD, who activate similar systems when listening to music, although there may be developmental differences in the physiological and neural response to music in childhood and adolescence alongside typical behavioral response [76].

Individuals with autism often have intact or superior pitch and timbre processing abilities, a phenomenon potentially linked to the functionality of the mirror neuron system (MNS) [70]. Wan proposes that engaging in music-making activities involving imitation and synchronization could activate brain regions that coincide with those housing mirror neurons [77]. Nevertheless, a debate persists regarding the role of mirror neurons in ASD [78]. Some studies have found that mirror neurons are normal in individuals with autism, while others proposed that a malfunctioning mirror neuron system in ASD contributes to difficulties in social communication and understanding the intentions of others [78].

**Table 1: A summary of research on the impact of music on autistic and normal individuals**

| Music Functions | Regular Group | Autism Group |
|---|---|---|
| Language acquisition | Second language [12], 2011 | Positive [66], 2017 |
| Phonological awareness | Positive [14], 2011 | No report |
| Pitch processing | Positive [22], 2007 | Positive [68], 2022 |
| Verbal fluency | Positive [24], 2011<br>No influence [25], 2014 | No report |
| Working Memory | Positive [12], 2011 | No direct research, Speculate positive |
| Reading | Diverse results [19], 2015, [20], 2022 | |
| Cognitive and social ability | Positive on auditory, cognitive control [12], 2011 | Positive on auditory [67], 2012 |
| | motor coordination [12], 2011 | Motor coordination [73], 2012, [79], 2018 |
| Social, emotional control | | Sensory stimuli [72], 2019<br>Reward, emotion [76], 2019<br>Anxiety, stress reduction [70], 2018, [75], 2020 |
| Neural mechanisms | Neural overlap [80], 2016<br>Neural networks [40], 2015<br>Structural Process [56], 2009<br>Bidirectional relationship [58], 2013<br>Cross domain and transfer effects [23], 2012<br>Brain plasticity [65], 2013 | Music is a unique domain for people with ASD [76], 2019<br>Mirror Neuron System activates a network of brain regions [81], 2010.<br>Debate on MNS [78], 2020<br>Distinct neural process, research is limited |

## 4. Musical training to enhance linguistic and cognitive skills in autistic children

The interplay between music and language is intricate and multifaceted, involving shared neural mechanisms and cognitive resources across these domains. These findings enhance our comprehension of the potential therapeutic advantages that music interventions can offer for enhancing language and cognitive development. The implementation of music therapy can be precisely tailored to accommodate the unique needs and preferences of children within the autism spectrum, rendering it a promising intervention for this particular demographic.

Jäncke [23] suggests that musical training could be beneficial in preventing, rehabilitating, and remedying various language, listening, and learning impairments. Many studies also explore the use of music interventions to enhance linguistic skills. The potential for cross-domain transfer effects between music and language have implications for the development of therapeutic interventions for language and cognitive development. Pino et al. reviewed the significant relationship between music and language, especially in early language development [82]. The study revealed that various musical aspects, like rhythm and melody, can influence language acquisition regarding semantic processing, grammar, syntax, and phonology.

Melodic Intonation Therapy (MIT) is a treatment program that uses the musical elements of speech, such as melody and rhythm, to improve language production in individuals with non-fluent aphasia [83]. This form of therapy involves several techniques, including intoned speech, sprechgesang (rhythmically emphasized prosody), unison production, and lip-reading. The program is designed to lead non-fluent aphasic patients from intoning simple, two to three syllable phrases to being capable of speaking five or more syllable phrases. This method applies musical elements to speech in order to improve language production by implementing melodic and rhythmic elements into speech in an exaggerated way that resembles singing. Vines et. al found that MIT in Broca's aphasics can be beneficial while simultaneously applying anodal transcranial direct current stimulation (tDCS) [84]. The study shows that the combination of right-hemisphere anodal tDCS with MIT can lead to better speech recovery outcomes.

Auditory-Motor Mapping Training: AMMT utilizes music-making methods with children with autism spectrum disorders This approach demonstrated promising results in assisting nonverbal children with autism in developing communication skills [77].

Rhythm-based interventions: Some music programs for autism employ rhythm-based interventions. These interventions focus on rhythm and timing activities to improve motor coordination, attention, and communication skills in individuals with ASD [79].

Parental support programs: Research studies have explored the benefits of promoting the musical engagement of autistic children in the early years through a parental support program. These programs involve providing parents with guidance and resources to facilitate musical interaction and engagement with their children [85].

In a study by Simpson [86], the utilization of music to heighten engagement in receptive labeling tasks for children with autism is explored. This investigation delves into the potential advantages of employing music to foster involvement among individuals with autism, consequently enhancing their task participation. Music can provide a way for children with autism to express themselves non-verbally. It can be a powerful tool for communication and self-expression. Music aids in assimilating sensory information among children with autism. This therapeutic approach can effectively target specific domains such as communication, social proficiency, and emotional regulation, presenting a methodical and nonverbal avenue for expression and interaction [71]. Given the diverse nature of ASD, music therapy can be meticulously tailored to accommodate the unique needs and preferences of children within the autism spectrum, rendering it a promising intervention for this particular demographic for this specific group.

The style of music training could be creating an environment with background music, singing songs, learning to play an instrument, and receiving music education. A study by Du et. al investigated the effects of background music on neural responses during the process of reading comprehension [87]. It was found that background music can induce a positive mood, increase stimulation, and overall improve reading comprehension. However, such effects may be varied depending on the types of background music played. Papadimitriou et al. suggested that singing and playing musical instruments can stimulate language development by encouraging vocalization, imitation, and expressive communication [88]. Linnavalli et al. also address that regular music lessons by professional teachers during early childhood education can improve children's phoneme processing and vocabulary skills like syllable discrimination, verbal memory, and prosody detection [89].

## Perspectives and conclusion

Music and language shared a strong correlation in terms of their origins, interaction and neural processing mechanisms. The analysis of archaeological discoveries, such as the Xun and ancient Chinese characters dating back to 4500 BC, suggests a possible coexistence and coevolution of music and language throughout early human history. Both domains underwent an evolution from simple styles to gradually becoming complex systems. These revelations shed light on the potential connection between music and language.

In addition, music and language exhibit structural similarities in syntax and the relationship between syllabic stress and music meter, suggesting that these two domains could engage similar neural process mechanisms.

The findings from neuroimaging techniques suggest that music and language processing involve overlapping neural mechanisms and shared cognitive and neural resources. Music and language processing have bi-directional influences with potential cross-domain transfer effects. These effects may be more pronounced for near-transfer skills, such as phonological awareness, than for far-transfer skills, such as reading comprehension.

The relationship between music and language is complex and multifaceted, involving the collaboration of various brain regions that can potentially activate neuroplasticity and dynamic changes in cognitive processes within the brain. This complexity makes it difficult to identify the specific neural mechanisms associated with each domain and to determine their interactions. Addressing these challenges requires the development of innovative methodologies that integrate psychology, neuroscience, cognitive science, computer science, linguistics, and affective science. Such interdisciplinary approaches are essential for unraveling the complexities of the intricate interplay between music and language.

Individuals with ASD often demonstrate retained or advanced music-processing abilities, showcasing superior pitch and timbre processing skills. This observation implies a unique neural circuitry that enables individuals with ASD to assess perception, reward, emotion, and their corresponding physiological reactions. Research has illuminated music's profound impact on the language, social, and communication skills of individuals with ASD. The positive effects of music on cognitive function among those with ASD suggest the existence of distinct neural processes tied to music, language, and cognition within this population. Studies of music therapy has placed a greater emphasis on enhancing social interaction and communication skills in ASD groups. Nevertheless, the precise role of music and the underlying neural mechanisms that shape language-related outcomes in ASD groups remain incompletely understood. Consequently, further interdisciplinary research is essential to gain deeper insights into the specific neural mechanisms and interventions that can enhance language and cognitive development among individuals with autism.

## Ethics approval and consent to participate

Not applicable.

## List of abbreviations

ASD: Autism spectrum disorder
CDC: Centers for disease control and prevention
ADDM: Autism and Developmental Disabilities Monitoring Network
OPERA: Overlap, Precision, Emotion, Repetition, and Attention
IFG: left inferior frontal gyrus
fMRI: Functional magnetic resonance imaging
SSIRHL: Shared Syntactic Integration Resource Hypothesis

N400 ERP: N400 event-related potential
EEG: electroencephalography
MEG: magnetoencephalography
MNS: mirror neuron system
MIT: Melodic Intonation Therapy
tDCS: transcranial direct current stimulation
AMMT: Auditory-Motor Mapping Training

## Conflicts of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationship that could be constructed as a potential conflict of interest.


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## Authors' contributions

EL conceived the idea, initiated and composed the manuscript. EL and WP conducted the literature search and summary, XF oversaw the manuscript preparation process. All authors critically reviewed and endorsed the final manuscript.


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## References


[1] American Psychiatric Association, “Diagnostic and Statistical Manual of Mental Disorders,” Fifth Edition (DSM-5), Textbooks, 2023. https://textbooksprime.com/product/diagnostic-and-statistical-manual-of-mental-disorders-fifth-edition-dsm-5-9780890425541/ (2023).

[2] Centers for Disease Control and Prevention, “Autism and Developmental Disabilities Monitoring (ADDM) Network, ” https://www.cdc.gov/ncbddd/autism/addm.html, 2023.

[3] T. R. Bellomo, S. Prasad, T. Munzer & N. Laventhal, “The impact of the COVID-19 pandemic on children with autism spectrum disorders,” J Pediatr Rehabil Med, vol. 13, pp. 349–354, 2020.

[4] J. P. Leigh, J. Du, "Brief Report: Forecasting the Economic Burden of Autism in 2015 and 2025 in the United States" J Autism Dev Disord, vol. 45, no. 12, pp. 4135-4139, 2015

[5] F. M. Besag, “Epilepsy in patients with autism: links, risks and treatment challenges,” Neuropsychiatr Dis Treat, vol. 14, pp. 1–10, 2017.

[6] M. J. Maenner et al., “Prevalence and Characteristics of Autism Spectrum Disorder Among Children Aged 8 Years - Autism and Developmental Disabilities Monitoring Network, 11 Sites, United States, 2018,” Morb Mortal Wkly Rep Surveill Summ Wash DC 2002, vol. 70, pp. 1–16, 2021.

[7] B. D. Barger & J. M. Campbell, “Developmental Regression in Autism Spectrum Disorders: Implications for Clinical Outcomes,” in Comprehensive Guide to Autism (eds. V. B. Patel, V. R. Preedy & C. R. Martin), Springer, pp.1473–1493, 2014, doi:10.1007/978-1-4614-4788-7_84.

[8] Z. Yanping, “The Early Neolithic in the Central Yellow River Valley, c. 7000-4000 BC,” in A Companion to Chinese Archaeology, pp. 169–193, 2013, doi:10.1002/9781118325698.ch9.

[9] S. Xu, "The History of the Xun –A 7000-Year-Old Instrument Rich in History and Culture,” Interact China, Spe 07, 2018.

[10] M. Wang et al. "Study on the evolution of Chinese characters based on few-shot learning: From oracle bone inscriptions to regular script" PLoS One, vol. 17, no. 8e0272974, 2022.

[11] J. Molino, “Toward an evolutionary theory of music and language.” In N. L. Wallin, B. Merker, and S. Brown (Eds.), The Origins of Music, pp. 165-176, 2000.

[12] R. Milovanov & M. Tervaniemi, “The Interplay between Musical and Linguistic Aptitudes: A Review,” Front Psychol, Vol 2, 323, 2011, doi: 10.3389/fpsyg. 2011.00321.

[13] C. Ott, N. Langer, M. Oechslin, M. Meyer & L. Jäncke, “Processing of Voiced and Unvoiced Acoustic Stimuli in Musicians,” Front Psychol, vol. 2, 195, 2011, doi: 10.3389/fpsyg.2011.00195.

[14] F. Degé & G. Schwarzer, “The Effect of a Music Program on Phonological Awareness in Preschoolers,” Front Psychol, 20 June 2011, doi:10.3389/fpsyg.2011.00124.

[15] M. M.Vidal, M. Lousada, & M. Vigário, “Music effects on phonological awareness development in 3-year-old children,” Appl Psycholinguist, vol. 41, pp. 299–318, 2020.

[16] E. Flaugnacco et al., “Music Training Increases Phonological Awareness and Reading Skills in Developmental Dyslexia: A Randomized Control Trial,” PLOS ONE, vol. 10, e0138715, 2015.

[17] D. Skubic, B. Gaberc, & J. Jerman, “Supportive Development of Phonological Awareness Through Musical Activities According to Edgar Willems,” SAGE Open, vol. 11, 21582440211021830, 2021.

[18] M. Sofologi et al., “Effectiveness of Musical Training on Reading Comprehension in Elementary School Children. Is There an Associative Cognitive Benefit?” Frontiers in Education, vol. 7, 875511, 2022.

[19] R. L. Gordon, H. M. Fehd & B. D. McCandliss, “Does Music Training Enhance Literacy Skills? A Meta-Analysis,” Front Psychol, vol. 6, 1777, 2015, doi: 10.3389/fpsyg.2015.01777.

[20] D. Temperley, “Music and Language,” Annu Rev Linguist, vol. 8, pp. 153–170, 2022.

[21] H. Aksoy, “The effect of music on reading skills: a meta-analysis study.” International Online Journal of Education and Teaching, vol.10, no. 2, pp. 740-763, 2023.

[22] M. Besson, D. Schön, S. Moreno, A. Santos & C. Magne, “Influence of musical expertise and musical training on pitch processing in music and language,” Restor Neurol Neurosci, vol. 25, pp. 399–410, 2007.

[23] L. Jäncke, “The Relationship between Music and Language,” Front Psychol, vol. 3, 123, 2012, doi: 10.3389/fpsyg.2012.00123.(2012).

[24] S. Moreno et al., “Short-Term Music Training Enhances Verbal Intelligence and Executive Function,” Psychol Sci, vol. 22, pp. 1425–1433, 2011.

[25] L. Jäncke, E. Brügger, M. Brummer, S. Scherrer & N. Alahmadi, “Verbal learning in the context of background music: no influence of vocals and instrumentals on verbal learning,” Behav Brain Funct, Behavioral and Brain Functions, vol. 10, 10, 2014, doi: 10.1186/1744-9081-10-10.

[26] D. L. Strait & N. Kraus, “Biological impact of auditory expertise across the life span: musicians as a model of auditory learning.” Hear Res, vol. 308, pp. 109–121, 2014.

[27] E. A. Miendlarzewska & W. J. Trost, “How musical training affects cognitive development: rhythm, reward

and other modulating variables," Front Neurosci, vol.7, pp. 279, 2013.
[28] M. Ettlinger, E. H. Margulis, and B.C. Wong, "Implicit memory in music and language." Front Psychol, vol. 2, 2011, doi: 10,3389/fpsyg.2011.00211.
[29] C. F. Mora, "Foreign language acquisition and melody singing," ELT J, vol. 54, pp. 146, 2000.
[30] S. Koelsch, "Toward a Neural Basis of Music Perception – A Review and Updated Model," Front. Psychol, vol. 2, 110, 2011.
[31] A. D. Patel & J. R. Daniele,"An empirical comparison of rhythm in language and music," Cognition, vol. 87, B35-45, 2003.
[32] K. Franich and A. Ngnemzue, "Feeling the Beat in an African Tone Language: Rhythmic Mapping Between Language and Music." Front Commun, vol. 6, 653747, 2021, doi: 10.3389/fcomm.2021.653747.
[33] E. E. Hannon, "Perceiving speech rhythm in music: Listeners classify instrumental songs according to language of origin," Cognition, vol. 111, pp. 403–409, 2009.
[34] R. L. Gordon, C. L. Magne & E. W. Large, "EEG Correlates of Song Prosody: A New Look at the Relationship between Linguistic and Musical Rhythm," Front Psychol, vol. 2, pp. 352, 2011.
[35] J. Clayton, "Prosodic Boundaries in Singing: An exploration of the temporal effects of linguistic structure in western music." Senior essay, Yale University Linguistics Department, Advised by K. Jelena and Q. Ian, 2 013.
[36] R. Jackendoff, "Parallels and nonparallels between language and music," Music Percept, vol. 26, pp. 195–204, 2009.
[37] L. R. Slevc & A. Miyake, "Individual differences in second-language proficiency: does musical ability matter?" Psychol Sci, vol. 17, pp. 675–681, 2006.
[38] D. Sammler & S. Elmer, "Advances in the Neurocognition of Music and Language," Brain Sci, vol. 10, pp. 509, 2020.
[39] E. Christensen, "The Neurosciences and Music: An Overview and Discussion," Bulletin of the Council for Research in Music Education, vol. 181, pp. 9-22, 2012.
[40] I. Peretz, D. Vuvan, M.-É. Lagrois & J. L. Armony, "Neural overlap in processing music and speech," Philos Trans R Soc Lond B Biol Sci, vol. 370, 20140090, 2015.
[41] G. F. Halwani, P. Loui, T. Rüber & G. Schlaug, "Effects of Practice and Experience on the Arcuate Fasciculus: Comparing Singers, Instrumentalists, and Non-Musicians," Front Psychol, vol. 2, pp. 156, 2011.
[42] L. Hoch, B. Poulin-Charronnat & B. Tillmann, "The influence of task-irrelevant music on language processing: syntactic and semantic structures," Front Psychol, vol. 2, pp. 112, 2011.
[43] A. D. Patel, "The OPERA hypothesis: assumptions and clarifications," Ann N Y Acad Sci, vol. 1252, pp. 124–128, 2012.
[44] A. J. Shahin, "Neurophysiological Influence of Musical Training on Speech Perception," Front Psychol, vol. 2, pp. 126, 2011.
[45] A. D. Patel, "Can nonlinguistic musical training change the way the brain processes speech? The expanded OPERA hypothesis." Hear Res, vol. 308, pp. 98–108, 2014.
[46] M. G. Jantzen, E. W. Large & C. Magne, "Editorial: Overlap of Neural Systems for Processing Language and Music," Front Psychol, vol. 7, 2016.
[47] A. Woessner, "Structural Processing Overlap: Music, Language, and the Brain," Brown University CLPS 1880: Topics in Psycholinguistics: Language + Memory, 1880D S01, 2016.
[48] I. Molnar-Szakacs & K. Overy, "Music and mirror neurons: from motion to 'e'motion," Soc Cogn Affect Neurosci, vol. 1, pp. 235–241, 2006.
[49] M. G. Jantzen, B. M. Howe & K. J. Jantzen, "Neurophysiological evidence that musical training influences the recruitment of right hemispheric homologues for speech perception," Front. Psychol, vol. 5, pp. 171, 2014.
[50] I. Peretz, "The biological foundations of music: Insights from congenital amusia." The psychology of music, Elsevier Academic Press, 3rd ed, pp. 551–564, 2013. doi:10.1016/B978-0-12-381460-9.00013-4.
[51] M. P. van den Heuvel & O. Sporns, "Network hubs in the human brain," Trends Cogn Sci, vol. 17, pp. 683–696, 2013.
[52] K. Grill-Spector & R. Malach, "fMR-adaptation: a tool for studying the functional properties of human cortical neurons," Acta Psychol, (Amst.), vol. 107, pp. 293–321, 2001.
[53] C. Rogalsky, F. Rong, K. Saberi & G. Hickok, "Functional anatomy of language and music perception: temporal and structural factors investigated using functional magnetic resonance imaging." J Neurosci Off J Soc Neurosci, vol. 31, pp. 3843–3852, 2011.
[54] M. T. Todd, L. E. Nystrom & J. D. Cohen, "Confounds in multivariate pattern analysis: Theory and rule representation case study." NeuroImage, vol. 77, pp. 157–165, 2013.
[55] D. Sammler, et al., "The Relationship of Lyrics and Tunes in the Processing of Unfamiliar Songs: A Functional Magnetic Resonance Adaptation Study," J Neurosci, vol. 30, pp. 3572–3578, 2010.
[56] E. Fedorenko, A. Patel, D .Casasanto, J. Winawer & E. Gibson, "Structural integration in language and music: Evidence for a shared system," Mem Cognit, vol. 37, pp. 1–9, 2009.
[57] S. Asaridou & J. McQueen, "Speech and music shape the listening brain: evidence for shared domain-general mechanisms," Front Psychol, vol. 4, pp. 1-12. 2013, doi: 10.3389/fpsyg.2013.00321.
[58] G. M. Bidelman, S. Hutka & S. Moreno, "Tone Language Speakers and Musicians Share Enhanced Perceptual and Cognitive Abilities for Musical Pitch: Evidence for Bidirectionality between the Domains of Language and Music," PLOS ONE, vol. 8, e60676, 2013.
[59] N. Calma-Roddin & J. E. Drury, "Music, Language, and The N400: ERP Interference Patterns Across Cognitive Domains," Sci Rep, vol. 10, 11222, 2020.
[60] M. Teichert & J. Bolz, "How Senses Work Together: Cross-Modal Interactions between Primary Sensory Cortices," Neural Plast, 538092, 2018, doi: 10.1155/2-18/5380921.
[61] E. Gamma, "Brain Plasticity (Neuroplasticity): How Experience Changes The Brain," Simplypasycology, July 11, 2023. https://www.simplypsychology.org/brain-plasticity.html.
[62] P. Mateos-Aparicio & A. Rodríguez-Moreno, "The Impact of Studying Brain Plasticity," Front Cell Neurosci, vol. 13, pp. 66, 2019.
[63] S. Moreno & G. M. Bidelman, "Examining neural plasticity and cognitive benefit through the unique lens of musical training," Hear Res,vol. 308, pp. 84–97, 2014.
[64] S. Wang & M. Agius, "The neuroscience of music; a review and summary," Psychiatr Danub, vol. 30, pp. 588–594, 2018.

[65] D. L. Merrett, I. Peretz & S. J. Wilson, “Moderating variables of music training-induced neuroplasticity: a review and discussion,” Front Psychol, vol. 4, pp. 606, 2013.

[66] A. M. Miller-Jones,”The Effect of Music Therapy upon Language Acquisition for Children on the Autism Spectrum Aged 3-8 Years,” ProQuest LLC, 2017.

[67] T. Ouimet, N. E. V. Foster, A. Tryfon & K. L. Hyde, “Auditory-musical processing in autism spectrum disorders: a review of behavioral and brain imaging studies,” Ann N Y AcadSci, vol. 1252, pp. 325–331, 2012.

[68] Y.Chen, E.Tang, H. Ding & Y. Zhang, “Auditory Pitch Perception in Autism Spectrum Disorder: A Systematic Review and Meta-Analysis,” J Speech Lang Hear Res, vol. 65, pp. 4866–4886, 2022.

[69] C. Rimmer, H. Dahary &E. M. Quintin, “Links between musical beat perception and phonological skills for autistic children.” Child Neuropsychol J Norm Abnorm Dev Child Adolesc, pp 1–20, 2023, doi:10.1080/09297049.2023.2202902.

[70] T. B. Janzen & M. H. Thaut, “Rethinking the role of music in the neurodevelopment of autism spectrum disorder,” Music Sci, vol. 1, 2059204318769639, 2018.

[71] R. James et al., “Music Therapy for Individuals with Autism Spectrum Disorder: a Systematic Review,” Rev J Autism Dev Disord, vol. 2, pp. 39–54, 2015.

[72] G. Bharathi, A. Venugopal & B. Vellingiri, “Music therapy as a therapeutic tool in improving the social skills of autistic children,” Egypt J Neurol Psychiatry Neurosurg, vol. 55, pp. 44, 2019.

[73] S. M. Srinivasan & A. N. Bhat, “A review of ‘music and movement’ therapies for children with autism: embodied interventions for multisystem development,” Front Integr Neurosci, vol. 7, pp. 22, 2013.

[74] E. Applebaum, A. L. Egel, R. L. Koegel & B. Imhoff, “Measuring musical abilities of autistic children,” J Autism Dev Disord, vol. 9, pp. 279–28, 1979.

[75] A. Bacon, C. P. Beaman & F. Liu, “An Exploratory Study of Imagining Sounds and ‘Hearing’ Music in Autis,” J Autism Dev Disord, vol. 50, pp. 1123–1132, 2020.

[76] E.M. Quintin, “Music-Evoked Reward and Emotion: Relative Strengths and Response to Intervention of People With ASD,” Front Neural Circuits, vol. 13, pp. 49, 2019.

[77] C. Y. Wan, K. Demaine, L. Zipse, A. Norton & G. Schlaug, “From music making to speaking: engaging the mirror neuron system in autism,” Brain Res Bull, vol. 82, pp. 161–168, 2010.

[78] L. Yates & H. Hobson, “Continuing to look in the mirror: A review of neuroscientific evidence for the broken mirror hypothesis, EP-M model and STORM model of autism spectrum conditions,” Autism, vol. 24, pp. 1945–1959, 2020.

[79] M. Shardaet al., “Music improves social communication and auditory-motor connectivity in children with autism,” Transl Psychiatry, vol. 8, pp. 231, 2018.

[80] M. G. Jantzen, E. W. Large & C. Magne, “Editorial: Overlap of Neural Systems for Processing Language and Music,” Front. Psychol, 14 June 2016.

[81] P. Gerrans, “Mirror neuron systems: The role of mirroring processes in social cognition,” Cognit Neuropsychiatry, vol. 15, pp. 501–504, 2010.

[82] M. C. Pino, M. Giancola & S. D’Amico, “The Association between Music and Language in Children: A State-of-the-Art Review,” Child Basel Switz, vol.10, pp. 801, 2023.

[83] A. Zumbansen, I. Peretz & S. Hébert, “Melodic intonation therapy: back to basics for future research,” Front Neuro, vol.5, pp. 7, 2014.

[84] B. W. Vines, A. C. Norton & G. Schlaug, “Non-invasive brain stimulation enhances the effects of melodic intonation therapy,” Front Psychol, vol. 2, pp. 230, 2011.

[85] T. Lisboa, C. Shaughnessy, A. Voyajolu & A. Ockelford, “Promoting the Musical Engagement of Autistic Children in the Early Years Through a Program of Parental Support: An Ecological Research Study,” Music Sci, vol. 4, 20592043211017360, 2021.

[86] K. Simpson, D. Keen & J. Lamb, “The use of music to engage children with autism in a receptive labeling task.” Res Autism Spectr Disord, vol. 7, pp. 1489–1496, 2013.

[87] M. Du, J. Jiang, Z. Li, D. Man & C. Jiang, “The effects of background music on neural responses during reading comprehension,” Sci Rep, vol.10, pp. 18651, 2020.

[88] A. Papadimitriou, C. Smyth, N. Politimou, F. Franco & LStewart, “The impact of the home musical environment on infants’ language development,” Infant Behav Dev, vol. 65, 10165, 2021.

[89] T. Linnavalli, V. Putkinen, J. Lipsanen, M. Huotilainen & M. Tervaniemi, “Music playschool enhances children’s linguistic skills,” Sci Rep, vol. 8, pp. 8767, 2018.