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RESEARCH ARTICLE

# Brain, musicality, and language aptitude: A complex interplay

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## Abstract

Music and language are highly intertwined auditory phenomena that largely overlap on behavioral and neural levels. While the link between the two has been widely explored on a general level, comparably few studies have addressed the relationship between musical skills and language aptitude, defined as an individual's (partly innate) capacity for learning foreign languages. Behaviorally, past research has provided evidence that individuals' musicality levels (expressed by singing, instrument playing, and/or perceptive musical abilities) are significantly associated with their foreign language learning, particularly the acquisition of phonetic and phonological skills (e.g., pronunciation, speech imitation). On the neural level, both skills recruit a wide array of overlapping brain areas, which are also involved in cognition and memory.

The neurobiology of language aptitude is an area ripe for investigation, since there has been only limited research establishing neurofunctional and neuroanatomical markers characteristic of speech imitation and overall language aptitude (e.g., in the left/right auditory cortex and left inferior parietal areas of the brain). Thus, as noted above, in this short review for ARAL, the aim is to describe the most recent neuroscientific findings on the neurobiology of language aptitude, to discuss the complex interplay between language aptitude and musicality from neural and behavioral perspectives, and to briefly outline what the promise of future research in this area holds.

**Keywords:** neurobiology of language; language aptitude; individual differences; language learning; musicality

Individual differences in language learning do not only manifest behaviorally, with some people being faster and more accurate at specific language learning tasks than others, but also manifest on the neural level. Such individual differences are thought to stem, at least partially, from variations in language aptitude. Aptitude was originally defined by Carroll (1981) as meaning an individual's initial capacity for acquiring foreign languages when motivation and opportunity are present. Clearly, a variety of factors (e.g., age of onset, learning conditions) are associated with foreign language learning success, and research has likewise suggested that musical skills interact with language learning abilities. Musicality (used here synonymously with musical skills) has been described as a set of skills that enables us to experience music emotionally, to understand it intellectually, and to create it ourselves (e.g., playing instruments or singing) (Gembris, 2013). Given the intricate links between language and music on behavioral and neural levels, it seems highly likely that musicality strongly influences language learning abilities and vice versa (e.g., see discussion in Turker et al., 2018).

Individual differences are omnipresent but are still often neglected in research (see, for example, Kidd et al.'s, 2018, recent summary from a psycholinguistic perspective). The initial state of the brain suggests individual differences are observable at all levels of analysis, ranging, for example, from molecular and synaptic differences to higher-level differences in functional systems and cognition (Zatorre, 2003). Since these differences might be indicative of specific abilities or skills already in pre (i.e., *in utero*), peri, and early postnatal stages (in the first years of an infant's life), it seems particularly worthwhile to consider multiple neural levels when trying to pinpoint neurobiological bases for language aptitude or musicality. Examples of neural differences are observable in gray and white matter volumes, cortical thickness (the depth of the layer of neurons on gyri, the bumps on the brain's surface, or sulci, the grooves on the brain's surface), cortical myelination (features of the lipid myelin sheath around neuronal axons that allow for fast information transmission between areas), gross structural brain morphology (number, shape, and depth of sulci and gyri), as well as structural (white matter fiber tracts connecting brain regions) and functional connectivity (brain areas working in concert during a task or during rest). While work in neurobiology has looked at these individual differences, there is a gap in the literature in terms of a thorough review of studies into the neurobiology of language aptitude and its interplay with musicality. So, the current review aims to summarize the most recent neuroscientific findings on individual differences in language learning and language aptitude and how musicality, in particular, interacts with speech comprehension and production and is manifested on the neural level. We briefly discuss how a model of language aptitude could implement musicality and outline some possibilities for future research in this area.

## The Neurobiological Basis of Language Aptitude

Numerous brain areas are engaged during linguistic processing, as noted by Price (2012). For a simplified illustration of the results of this work, see Figure 1. These are all potentially relevant for language aptitude (as noted in Biedroń, 2015). Second language learning success has been linked to various neurobiological patterns and mechanisms, ranging from differences in gray matter volumes and cortical thickness, variation in the structural connections of language-specific regions, functional activation and connectivity within these areas, as well as in functional connectivity differences during rest (for a summary, see Li & Grant, 2016). In terms of brain anatomy, three critical regions—namely, the bilateral auditory cortices (see AC in Figure 1), the left inferior parietal lobe (IPL), and the left inferior frontal cortex/gyrus (IFC/IFG)—have been successfully linked to high language learning abilities. These regions are all shown in Figure 1.

The auditory cortex, responsible for primary auditory analyses and directly related to phonological processing, might be a source of individual differences in speech processing (as proposed in Golestani, 2014; Golestani, et al., 2011). A recent longitudinal study showed that auditory cortex anatomy, comprising primarily the first transverse temporal gyrus (also called Heschl's gyrus), remains stable in children irrespective of musical training (e.g., Seither-Preisler et al., 2014; Serrallach et al., 2016), pointing toward a strong genetic contribution. Golestani et al. (2002, 2006) and Golestani and Pallier

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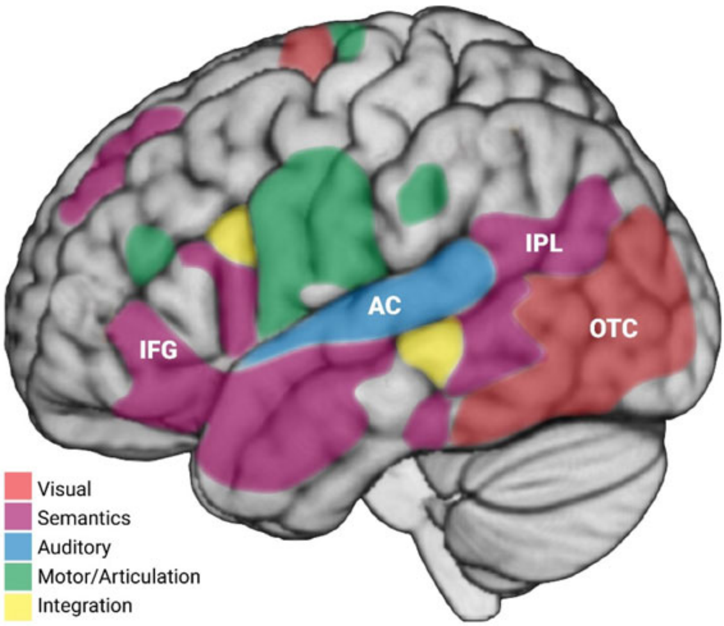


**Figure 1** A simplified illustration of left-hemispheric areas relevant for language processing as found in the review by Price (2012)
Note: (AC = auditory cortex, IFG = inferior frontal gyrus, IPL = inferior parietal lobe, OTC = occipito-temporal cortex)

(2007) reported that faster novel speech sound learning was linked to higher white matter density in the left auditory cortex (Golestani et al., 2011), while faster phonetic learners showed a greater leftward asymmetry for white matter density in the inferior parietal lobe. Higher gray and white matter volumes in the left auditory cortex were also confirmed in expert phoneticians (Golestani et al., 2011), potentially due to their intense life-long training and work in phonology and/or innate potential. An association between high speech imitation skills, language aptitude, and the possession of multiple Heschl's gyri[1] (i.e., the occurrence of multiple transverse gyri in the auditory cortex) was also found in children's, teenagers', and adults' right auditory cortices (Turker, 2019; Turker et al., 2017, 2019). In the same studies, possessing a single gyrus correlated with particularly low scores on the language aptitude tests. Higher gray matter volumes in children and teenagers' right auditory cortices predicted their overall scores in language aptitude testing. Multiple gyri provide a higher surface area for auditory and phonological processes, and this could be advantageous for all auditory-related functions, as well as structural connections to other relevant brain areas. Due to limited research in the area, though, it is unclear which function these additional gyri have, whether they influence the (development of) structural connections between brain areas, and whether they have an impact on functional connectivity.

Looking at structural differences in the inferior parietal lobe, Della Rosa et al. (2013) confirmed that successful language learners had increasing gray matter density in the left inferior parietal lobe over a one-year period, suggesting that this area is critically engaged in foreign language learning outcomes. Functionally, the left inferior parietal lobe is further indicative of second language reading speed (Barbeau et al., 2017).

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Golestani and Pallier (2007) found that learning to pronounce a foreign consonant correlated with higher white matter density in the left insula/prefrontal cortex and the inferior parietal lobe bilaterally. The inferior frontal gyrus is a hub for neural activities (Yang & Li, 2012), and differences therein have been further related to tonal vocabulary learning (Yang et al., 2015), lexical pitch learning (Qi et al., 2019), and statistical word segmentation learning (Karuza et al., 2014). Increased cortical thickness in this area has also been linked to second language learning in children (Klein et al., 2014). Recently, Novén et al. (2019) reported that grammar learning (measured as grammatical inferencing in a language aptitude test) correlated positively with cortical thickness in pars triangularis of the left inferior frontal gyrus and the left medial superior frontal gyrus.

### The Neural Correlates of Individual Differences in Language Learning

Findings on the neurofunctional underpinnings of individual differences in language learning have been varied so far. Reiterer et al. (2005), for instance, reported systematic differences between high and low-proficiency speakers in the alpha frequency band (neural oscillations covering a frequency of 813Hz), as well as a coherence increase in all electrodes over language areas in the left hemisphere in those with poor language proficiency. In a large-scale study, Reiterer and colleagues (Dogil & Reiterer, 2009; Reiterer et al., 2011) argued that speech imitation ability has a distinct neurofunctional/neuroanatomical signature. Those with low speech imitation ability displayed higher brain activation in left frontoparietal network during sentence production, while those with high speech imitation ability showed higher gray matter volumes and decreased task-related brain activation in the same areas. They found a main effect for aptitude in a network spanning the core language areas in the left hemisphere. The results showed that advanced pronunciation aptitude was associated with higher activation in both speech-motor and auditory-perceptual areas (also found in Hu et al., 2013).

Investigating novel grammar learning, Kepinska, Pereda, et al. (2017) compared brain measures of individuals with high and average language analytical abilities while performing an artificial grammar learning task. They found that highly skilled learners had a steeper learning curve, higher ultimate attainment, and showed less mental effort. Neurally, three regions were less engaged in average learners, namely the right supramarginal/angular gyrus (IPL in Figure 1), the left cingulate gyrus (an area in the medial aspect of the brain), and the right superior and middle frontal cortex (regions above IFG in Figure 1) (Kepinska, de Rover, et al., 2017a). When comparing functional connections between these areas, the authors found major group-related differences in the task-positive/language network (i.e., the areas simultaneously active during a linguistic task), the default mode network (a network of brain areas more active during rest than during tasks; Raichle, 2015), and the working memory network (Kepinska, de Rover, et al., 2017b).

### Further Studies on Brain Networks, Synchronization and Connectivity

Focusing on individual differences in speech comprehension, Prat and colleagues have reported in a number of studies that individual differences in language learning manifest in differences in neural efficiency, neural adaptability, and functional synchronization across various right and left-hemispheric brain areas (Prat, 2011; Prat et al., 2007). Their recent results suggest that successful intensive language learning depends upon pre-existing coherence and EEG power spectra between right frontotemporal areas (Prat et al., 2016; 2019). These two elements correlate with more accurate speech during/after learning and L1 abilities (Prat et al., 2016; 2019). Additionally, brain state rhythms (detected by measuring resting state EEG spectral power and coherence patterns), especially in the higher frequency ranges (beta and gamma), predicted between 26–60% of variance in language learning abilities/aptitude (Prat et al., 2016; 2019). The fact that the high-frequency (fast waves) gamma range in EEG in particular affects different stages in foreign language learning expertise (stronger and broader gamma coherence/network patterns occurring in lower L2 proficiency individuals in frontoparietal networks), confirms earlier findings (Reiterer, Pereda et al., 2011). This is particularly interesting because brain state rhythms (e.g., resting, activated) have been shown to reflect individual characteristics of different levels of ability in language learners (Assaneo et al., 2019). This individual difference is most prominent in especially state rhythms that are task-unrelated but person-related (like resting-state rhythms), creating rhythmic brain signatures that are potentially significant contributors to cognition (Assaneo et al., 2019). Neural oscillations (i.e., neurally rhythmical pacemakers) are increasingly being seen to have a fundamental role in perception and cognition, since the speech motor cortex can be seen as a neural oscillator that reflects acoustic speech regularities internally in the brain (Poeppel & Assaneo, 2020).

Other studies addressing task-related and resting-state functional connectivity in the context of language learning success found that intrinsic connectivity within posterior temporal areas predicts second language learning capacity (Chai et al., 2016) and that higher global network efficiency, as well as distinct network patterns, are indicative of word learning success (Sheppard et al., 2012). Successful implicit language learners were also reported to have stronger connections between the right and left supramarginal gyri, although functional connectivity patterns changed with the learning process and success (Veroude et al., 2010).

Finally, white matter fiber tracts and their link to language aptitude have been investigated in few studies. Xiang et al. (2012), for example, found that the white matter fiber tracts between the core language areas were differentially related to language aptitude subskills and domain-general cognitive abilities. The number of streamlines (i.e., the strength of the pathway) connecting the left anterior inferior frontal cortex and the posterior temporal cortex predicted vocabulary learning, whereas connections in the left and right premotor-temporal pathway predicted grammatical inferencing. Sound-symbol correspondence was best predicted by the interhemispheric connections of the left inferior frontal cortex. Similarly, Kepinska, Lakke, et al. (2017) found that the magnitude of diffusion (of water molecules) of the right anterior, the left long and the left anterior segment of the arcuate fascicle could correctly classify high-level learners with an accuracy level of 78%. Additionally, Vaquero et al. (2017) reported that a larger lateralization of the arcuate fascicle volume toward the left was predictive of speech imitation performance. The higher the white matter volume in the right arcuate fascicle, on the other hand, the lower the imitation performance.

### Individual Differences on the Subcortical Level

In addition to individual differences on the cortical level (i.e., the most superficial layer of the human brain), the subcortical level, comprising neural formations within the brain (e.g., basal ganglia, limbic system, cerebellum), may be indicative of higher-level language learning capacities as well (e.g., for the encoding of nonnative phonemes; Kraus & Chandrasekaran, 2010) or vocabulary learning (Breitenstein et al., 2005). Implicit learning systems are vital for foreign language learning (Ullman, 2016) and rely primarily on subcortical structures, such as the basal ganglia (Wong et al., 2012). A major debate, however, is to what extent procedural (implicit) and declarative (explicit) memory are really predictive of ultimate attainment (Skehan, 2019). Studies by Morgan-Short et al. (2014), for example, suggested that procedural learning can predict ultimate attainment in late-stage learners, while declarative learning is indicative of early-stage learning success.

## The Behavioral Relationship Between Musical Abilities and Language Aptitude

Language and music are two abilities that have been extensively researched, in particular with regard to their similarities and differences (see also recent summaries by Sammler, 2020 or Turker, et al., 2018). On a very simple level, both can be described as auditory phenomena that are conveyed by sounds and are mostly specific to humans. They are not simply sounds but structural systems that consist of sequential events that unfold in time and follow some form of hierarchical organization. Both music and language learning are used for expressing emotions, thoughts, knowledge, and intentions. In the case of comparing singing and language production in speech, both systems even share the same anatomic production system: the vocal tract apparatus plus the lungs and certain brain representations (for more details, see Besson & Schön, 2001 and Jackendoff, 2009). Given the numerous similarities between the two, it does not seem surprising that the two often also interact (e.g., language is based on musical qualities like vocal timbre, intensity, rhythm), and music is often accompanied by language in the form of singing. A salient differentiation between the two domains seems to remain in the use of pitch and melody, because musical melodies exploit pitch ranges and variabilities disproportionally more than languages, where the range of pitch variability is rather limited (Chow & Brown, 2018).

Since language and music are so similar, many researchers have already explored the relationships between specific linguistic abilities, or, to be more specific, between speech production or comprehension and musical abilities and/or training. If we take a closer look at the relationship between speech perception and musicality, we find that there is evidence for a relationship between pitch perception and speech perception, for instance. In several studies, professional musicians were more successful at detecting differences in pitch in both language and music (Besson et al., 2007; Burnham et al., 2015; Marques et al., 2007; Schön et al., 2004). In another study, Bowles et al. (2016) found that pitch ability was a better predictor for second language aptitude in a tone language than general musicality and other cognitive abilities. They thus raised the claim that it might not be general musicality, but rather specific musical traits that could predict advantages for second language learning. Studies by Delogu et al. (2006, 2008), on the other hand, suggested that melodic abilities and overall musical training led to enhanced discrimination of lexical tones. Recent studies also found that overall musicality was driven mostly by melody discrimination ability and predicted second language reading fluency skills in learners of Spanish as a foreign language (Foncubierta et al., 2020).

Apart from pitch processing, differences in rhythm perception have been linked to speech comprehension. Nardo and Reiterer (2009), for instance, found that rhythm perception was linked to pronunciation talent (or "phonetic talent" as they called pronunciation aptitude in their work) in the second language and grammatical sensitivity, as measured by the Modern Language Aptitude Test (MLAT; Carroll, & Sapon, 1959). Bhatara et al. (2015) also found that rhythm perception was linked to a higher amount of musical training and more foreign language learning experience. It seems that either more intensive experiences with music and language lead to better rhythm perception, or very good rhythm perception facilitates (or fosters interest in) language learning and musical training.

The relationship between speech production skills and musical abilities has been less extensively researched to date, but the few studies that have been conducted have shown overall very promising results. Milovanov et al. (2008, 2010) found, in several studies, that subjects with more musical training and higher musicality had a better pronunciation in their second language. They could back these results on the neural level and showed that those with higher pronunciation and musicality skills also showed more prominent sound-change-evoked brain activation to musical stimuli. Similarly, two other studies have shown that there was a highly positive relationship between specific musical abilities and second language pronunciation (Slevc & Miyake, 2006; Dolman & Spring, 2014). Aiming for similar results, Vangehuchten, Verhoeven and Thys (2015) looked into pronunciation and prosody skills in Dutch Spanish as L2 learners. However, they only found a relationship between receptive musical and receptive language skills, with good receptive auditory capacity going hand in hand with phoneme and stress-pattern reception in the Spanish L2 learners. Exploring foreign language learning through music, Ludke et al. (2014) reported that singing can facilitate phrase learning in an unfamiliar language, so that those students who used a listen-and-sing strategy had better results in recalling vocabulary. Musical skills further correlated highly with speech imitation, accent faking in the first language, reading abilities, vocabulary proficiency, and grammar aptitude (Reiterer, 2018, 2019). Christiner and Reiterer (2013, 2015) also found that, specifically, singers seem to have an advantage in pronunciation, since singers outperformed instrumentalists and nonsingers/noninstrumentalists in their study.

### Shared Neural Resources for Language and Music

Taking a closer look at the neurobiology of language and music, it becomes clear that both recruit an array of brain networks that involve visual, auditory, motor, and memory-related processes. Kraus and Chandrasekaran (2010) summarize that musical training shows substantial benefits both at subcortical and cortical levels, since it leads to stronger brainstem responses to features like pitch (also discussed in Moreno & Bidelman, 2014 and Wong et al., 2007). Furthermore, musicians seem to possess enhanced perceptual, language, and high-level cognitive processing (Moreno et al., 2011; Roden et al., 2012; Schellenberg, 2011).

Because language learning is such a natural process, it is hard to elucidate the specific advantages and changes associated with it. Musical training, however, could be shown to have positive and long-lasting benefits on auditory functioning, while at the same time leading to morphological differences in the precentral gyrus, motor areas, and auditory cortices (Kraus & Chandrasekaran, 2010). A particularly interesting overlap on the neural level was initiated by research conducted by Seither-Preisler et al. (2014), who investigated the role of the primary auditory cortex for musical skills, literacy, and attentional skills. They reported that a large right Heschl's gyrus signified high musical potential and was particularly important for the processing of suprasegmental, slowly changing acoustic cues. In their study, high musical practicers (i.e., individuals who play instruments or sing regularly) showed a faster and more intense processing of auditory input and a better interhemispheric synchronization. Through their longitudinal research, the authors could provide evidence that auditory cortex morphology was largely genetically determined and significantly associated with musicianship/high musical practice. They thus concluded that pre-existing anatomical factors, together with heightened efficiency due to these anatomical differences, would (under the right circumstances) develop into an outstanding competence for successful second language acquisition.

To summarize, it seems that specific musical abilities, such as rhythm or melody perception, are positively linked to speech production and/or comprehension. This is most likely caused by the large neural overlap between language and music, specifically the potential of music (through musical training or already present high musicality) to enhance language-relevant skills (e.g., auditory discrimination, attention, memory).

## Summary and Conclusions

To date, very few studies have explicitly looked into the neurobiology of language aptitude, mostly confirming the importance of the inferior frontal cortex/inferior frontal gyrus, the inferior parietal lobe, and auditory areas for individual differences in language learning. Moreover, the structure of major fiber tracts connecting language-related regions might be related to either very high or low performance on language aptitude tests. Structural differences in the form of gray matter volumes and gross morphology have been found in the right auditory cortex and the right inferior frontal cortex, but they are likely genetically determined and not experience-dependent.

Regarding the functional activation profiles associated with high aptitude, it seems that either widespread activation (drawing upon more resources) or particularly less activation (more efficient processing) characterize especially gifted language learners, potentially due to differences between applied tasks. Typically, a reduction in intensity of activation after initially higher activation levels is observed with increasing "habituation." Thus, measurements at different stages of expertise (different tasks and individuals involved) could be responsible for the observed inconsistencies. Moreover, resting-state functional connectivity, as well as task-related functional connectivity, can reveal important insights into overall learning aptitude. The role of subcortical structures for implicit and explicit language aptitude, on the other hand, has not been explicitly addressed in neuroscientific research to date. Due to the role of subcortical regions for learning, it seems worthwhile to explore if and to what extent subcortical structures influence or interact with language aptitude.

Research has shown that musicality or high musical abilities are likely to be part of the cognitive starter kit for auditory processing and thus intricately tied to an innate language aptitude profile. This would explain why we often observe a strong relationship between musical ability and language learning in the absence of musical training or musicianship. Musical training has clearly been shown to enhance general auditory processing and positively influence language learning, suggesting that, even at later stages and in the potential absence of excellent musicality or musical processing abilities, learning to play an instrument or to sing could benefit the foreign language learning process in a variety of ways, most obviously on the neural level. It thus seems to be the case that, though musicality and musical training are not necessary for language aptitude to develop and unfold, they certainly have the potential to significantly enhance language learning abilities. Thus far, research has indicated their impact may be related to specific subskills of language (e.g., speech comprehension as phonetic coding ability) but not language aptitude as a whole, per se.

While the large behavioral and neural overlap and interaction between musical abilities and language learning has been extensively researched, there is a complete lack of studies (in particular, longitudinal ones) exploring language aptitude in young children and adolescents, meaning that there is practically no research to date on how language aptitude develops on the neural and behavioral level from infancy to child and adulthood. This would be particularly interesting with regard to the role of musical training or musical skills from early stages to later language learning. We therefore suggest investigating language aptitude (behaviorally and with neuroimaging techniques) in very young children at early stages of (first/foreign) language learning and observe changes over the lifespan to further develop our current understanding of the neurobiology of language aptitude and musicality.

## Notes

1 The auditory cortex is the brain region where incoming auditory and acoustic information is primarily processed (spectrotemporal analysis). Most people possess one single gyrus where this primary analysis takes place, namely Heschl's gyrus.

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