Aud Vestib Res (2019);28(3):134-145.

REVIEW ARTICLE

The impact of music on auditory and speech processing

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Received: 22 Sep 2018, Revised: 27 Oct 2018, Accepted: 11 Nov 2018, Published: 15 Jul 2019

Abstract

Background and Aim: Researchers in the fields of psychoacoustic and electrophysiology are mostly focused on demonstrating the better and different neurophysiological performance of musicians. The present study explores the impact of music upon the auditory system, the non-auditory system as well as the improvement of language and cognitive skills following listening to music or receiving music training.

Recent Findings: Studies indicate the impact of music upon the auditory processing from the cochlea to secondary auditory cortex and other parts of the brain. Besides, the impact of music on speech perception and other cognitive processing is demonstrated. Some papers point to the bottom-up and some others to the top-down processing, which is explained in detail.

Conclusion: Listening to music and receiving music training, in the long run, creates plasticity from the cochlea to the auditory cortex. Since the auditory path of musical sounds overlaps functionally with that of speech path, music helps better speech perception, too. Both perceptual and cognitive functions are involved in this process. Music engages a large area of the brain, so music can be used as a supplement in rehabilitation programs and helps the improvement of speech and language skills.

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Keywords: Auditory processing; speech perception; music

Citation: Moossavi A, Gohari N. The impact of music on auditory and speech processing. Aud Vestib Res. 2019;28(3):134-145.

Introduction

Infants are inherently inclined to learn the language. Naturally, they turn fluent by the age of 3 or 4 and acquire all necessary skills for speech processing. All normal humans inherently have an aesthetic sense of music and can enjoy it. According to Wilson, "while language acquisition occurs rapidly and mainly automatically in children, music is learned more slowly and demands considerable training and practice." He then concluded that music probably drove from language [1]. The auditory system plays a fundamental role in learning music and is, therefore, a system mostly changed under music training. Functional and structural changes occur in different points of the auditory path, from the brainstem [2] to the primary cortex and associated areas [3], as well as those areas involved in high-order auditory processing [4].

Music is defined either as "the art of vocal or instrumental sounds combination to generate beauty of form and emotional expression" or "the art or science of ordering of sounds in notes and rhythms to produce a pleasant pattern or effect" [5]. Music is a source of pleasure, learning, and well-being and a potent stimulus for the brain. Developments in modern imaging techniques within the last few decades revealed what exactly happens in the brain while someone listens to music or plays and feels it, and how the structure and functions of the brain change due to music training. Much evidence supports that in a healthy brain, a big bilateral network, involving temporal, frontal, parietal, cerebellum, limbic, and paralimbic areas is related to auditory perception, language, syntactic and semantic processing, attention, working memory, semantic memory, episodic memory, rhythmic and kinetic functions. Additionally, emotions are all influenced by music processing [6] and this neural network is formed by music training [7].

"Music effects" are frequently ascribed to the training-related plasticity. Findings on both from human and animal studies indicate that the nervous system is highly capable of reorganizing its functions under auditory training and this capability manifests positively in daily communications [8-10]. Music engages sensory, cognitive, and reward networks of the brain. These networks are widely extended and their integrated function stimulates neural plasticity. Listening to music not only manifest it's neurophysiological but also its cognitive benefits. These advantages are seen in memory and auditory attention [11-13], general intelligence, executive functions [14,15], speech perception in noisy environments [16,17], language processing [18], and reading and writing abilities (literacy) [19].

Language is a symbolic medium for communication. Humans do not speak merely to be heard but they speak to be understood. They talk about a variety of things by means of language. Speech is therefore said to be symbolic and sound carries messages. The same stimulus may be perceived as music or language depending on the way one hears it. Repeatedly listening to a recorded speech makes it seem like a song [1].

Some findings suggest the difference between adults' brain areas in responding to speech and song. These areas become more specialized by the development of the brain. According to the findings, there is an overlapping activation between instrumental music and infant-directed speech in infants [1]. Music and speech are complex auditory signals of similar acoustic parameters: frequency, duration, intensity, and timber. The building blocks of language are morphology, phonology, semantics, syntax, cognition, and function and those of music are rhythm, melody, and harmony. Perception and production of both music and speech require memory capabilities and sensory-motor abilities. It has been proved that music and language share common neural resources for prosody, syntax, and semantic processing. Music specialization leaves a positive effect on different aspects of speech processing such as prosodic modality, segmental, and supra-segmental vocalic discriminations, and speech rhythmic structure. Most importantly, these kinds of benefits are reported both for mother tongue and foreign language [20]. There is also some evidence that skills learned through music training will affect speech perception and improves speech perception [21]. Vocal training accompanied by music training sharpens social and language skills [22]. Patel developed OPERA hypothesis to justify the impact of music upon speech. It is stated that the overlap between language and music networks makes music training beneficial. Music involves precise auditory process as well as interest, repetition, and attention, too [23].

Since music is reported to have various positive effects, exploring the impacts of music upon the auditory system will increase our neurophysiologic knowledge, and establish the position of music in auditory rehabilitation programs. The present study initially examines the neurophysiological impact of music training on auditory processing and afterward, by applying physiologic and electrophysiological tests, the effects on speech perception are investigated. Last but not least, further hypotheses are introduced regarding the neurophysiologic implications of listening to music and receiving music training for speech perception.

Impacts of music on physiological and electrophysiological auditory processing cochlea

Cochlea receives efferent feedback from the medial olivocochlear bundle (MOCB). This path initiates from superior olivary complex within the caudal brainstem and culminates in outer hair cell. Efferent fibers innervate from superior olivary complex to the contralateral cochlea. Accordingly, an indirect connection between the two ears is formed [24].

Presently, the most common objective method for the examination of the efferent system is transient evoked otoacoustic emission (OAE) suppression which enables the examination of the internal medial olivocochlear bundle [25]. In this method, the broadband noise, 1.5 dB over the threshold, is applied to the contralateral ear and the otoacoustic amplitude of the contralateral ear is registered. The normal limit is 0.5 to 1 dB reduction [24]. Cross-sectional studies investigating OAE suppression in musicians and non-musicians have found greater contralateral suppression in musicians [26]. Whereas the efferent function of the internal medial olivocochlear bundle in human auditory ability is understudied, it is considered effective in the realm of listening in the real world. For example, activities of the internal medial olivocochlear bundle help the improvement of auditory ability in non-favorable conditions and act as anti-mask [25], so that it improves signal in noise detection [27], speech in noise perception [28], and behavioral discrimination accuracy [29]. Damage in this part is reported as a reason for auditory processing disorder [30]. It seems that music training affects primary stages of sensory-auditory processing through top-down efferent feedback from the brainstem to the environment and improves hearing speech sounds in unfavorable acoustic conditions.

Brainstem

Anatomy of the brainstem

Brainstem is a necessary relay in the auditory pathway which processes signal prior to the processing in the brain. The brainstem is where auditory reflexes, sound lateralization, and multi-modal integration occur in different points and it involves sound lateralization and identification ascending pathway to the auditory cortex. Temporal fluctuations, spectral contrasts, and sound localization are represented in numerous cores of this part [31].

In a recent study investigating subcortical evoked potentials, frequency following response (FFR) indicates a prominent role in experience-based plasticity [32]. FFR is a stable neuro-microphonic potential that reflects dynamic and phase-locked activity to periodical features of complex acoustic stimuli (e.g. music and speech) [33,34]. The amplitude of this kind of evoked response increases significantly by attention [35]. Training, either in the field of music or speech, enhances FFR amplitude. This increase which indicates better Fundamental Frequency (F0) in brainstem has been already detected in musicians exposed to music stimulation [36]. Musicians also show stronger and more precise subcortical encoding of the language pitch compared to non-musicians [2]. The accuracy in brainstem response to stimulation frequency enhances in those who speak a tonal language. Besides, musicians can better encode language tone and those who speak the tonal language do better in music processing. This reciprocity shows that differences due to experience-based plasticity are typical of the brainstem function. However, cortical efferent mechanisms may also be involved in FFR responses [37].

Precise segregation of closure consonants in speech auditory brainstem response (ABR) tests in musicians, contrary to non-musicians, is in line with the results of working memory and attention [38]. Neural responses with shorter latency and less jitter are more prominent in musicians in comparison with non-musicians. This issue proves that music both enhances subcortical activity output and change its neurophysiological process by increasing temporal accuracy [39]. Another study on brainstem indicate that two years of participation in group music programs improves neurophysiologic discrimination of speech similar sounds during active and passive listening and advantages of music training will transfer to non-music areas [40]. The literature review indicates that those children who can better read and perceive sound in noise demonstrate stronger neural discrimination of

vocal syllables in the brainstem [41-43].
On the whole, music and speech training causes neuroplastic changes in FFR and speech ABR of the brainstem. In addition, musicians show better encoding to speech stimulations, so some function exchange between speech and music domain at brainstem seems logical. However, the role of the corticofugal efferent system, especially regarding attention, must be considered.

Primary auditory cortex
Auditory cortex located in superior temporal lobe plane is hidden by Sylvian or lateral sulcus. The primary auditory cortex is located within the dorsolateral and Heschl's gyri and in Brodmann area 41 [44]. Middle latency response (MLR) sends thalamocortical input to primary auditory cortex and reflects processing at this level. This cortical response consists of Na/Pa/Nb/Pb components which usually occur between 15 and 60 ms following sound onset [45]. Although training music or speech both target FFR [36], there is not enough evidence for such functional overlap in the primary auditory cortex which is represented by MLR index [45].
The amplitude and encoding of rhythm and pitch for pure tone and music sounds in MLR was higher and more precise in musicians than non-musicians [46,47], but it was not the case in perception and instruction of speech. Since under natural circumstances people are more exposed to voiced speech than unvoiced one and music training as well impacts on MLR, it can be expected that voiced stimuli evoke bigger MLR amplitude than unvoiced stimuli. It is found that M50 amplitude (the equivalent of P1) is smaller for semi-speech voiced stimuli in comparison with unvoiced stimuli but M100 amplitude (the equivalent of N1), which has some origin in the secondary auditory cortex, is bigger for semi-speech voiced stimuli in comparison with unvoiced ones [48]. On the other hand, when voice onset time (VOT) is applied to adolescents, smaller P1 amplitude and bigger N1 and P2 amplitude are achieved. These findings all prove that speech pitch processing initiates at higher cortex than that of music [49].
According to the findings, MLR bigger amplitude indicates neuroplastic changes in temporal (rhythm) and spectral (pitch) processing following music training and the change of MLR components with basic acoustic indexes is evident. Higher cortical areas (i.e. secondary auditory cortex) are specific for the processing of signals such as speech which are temporally-spectrally more complex.

Secondary auditory cortex
The secondary auditory cortex is located around primary auditory cortex and entails belt and parabelt areas which are extended from superior temporal plane to superior temporal gyrus [31]. It is supposed that N1 and P2 responses derive from auditory electric late responses from the secondary auditory cortex [50].
The amplitude of N1, P2 enhances both in non-musicians following auditory training and in musicians following continuous practice in music [51]. In addition, the responses of those who had received music training to speech stimulation occur by reduced latency [52,53]. It was found that acoustic training in the field of speech generates bigger P2 amplitude. In a recent study, following short-term instruction of vowel discrimination tasks based on F0 manipulation, bigger P2 amplitude was detected [54]. Enhanced P2 amplitude following VOT discrimination instructions was reported as well [55].
The potential of P3 occurrence, the impact of musical activities within home up auditory processing of infants in terms of features, including frequency, duration, lateralization, interval, and intensity were evaluated. It was found that P3 amplitude enhances following more musical activities and a positive correlation is discerned between musical activity within the home and better auditory discrimination based on mismatch negativity (MMN) [56]. The positive impact of music intervention is transferable to speech stimulation and in infancy (the first 9 months) results in higher MMN amplitude. Bigger MMN amplitude is achieved in response to change in the temporal structure of music in the auditory and prefrontal cortex [57]. Besides secondary auditory cortex, an increase in the amplitude of

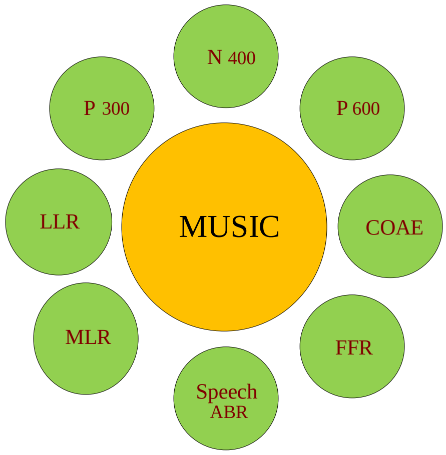

Fig. 1. Physiologic and electrophysiologic responses are affected by music.

N400 and P600 are reported in musicians, which is indicative of improved function [37].
These studies show music training facilitates cortical responses to speech-related signals in the long term. These changes, which may be due to the effect of cognitive processing, play a critical role in transferring functions of music and speech. Fig. 1 shows different types of physiological and electrophysiological responses from primary processing levels to higher cognitive levels following musical activities.

The neurophysiological impact of music upon the structure of language and speech structure

Musicians, compared to non-musicians, show stronger neural responses to complex tones of resolved and unresolved harmonics. Increased responses in the right hemisphere, including right superior temporal gyrus, Heschl's gyrus, insular cortex, inferior frontal gyrus, and colliculus inferior is evident. Findings indicate two levels of neural plasticity in musicians. Changes in pitch processing increase in follicular and right auditory cortex. Enhanced responses in the right hemisphere of musicians ratify this attitude so that right auditory cortex acts more sophisticated than left auditory cortex in processing fine pitch. Higher activation in insular cortex, right superior frontal gyrus, and right inferior frontal gyrus of musicians can be interpreted as higher involvement of neural resources for extraction, preservation, and comparison of pitch information [58].
Generally, speech processing is assumed to be modified initially in the auditory cortex of the brain. This claim is based on study that examined functional-neural anatomy of speech perception [59]. Speech phonologic processing involves a network in superior temporal sulcus (SIS) in the left hemisphere [60]. Speech semantic processing which includes retrieving the correct meaning of words takes place in a network located in left inferior temporal gyrus [61] and frontal gyrus [62].
The well-known asymmetric sampling in time (AST) hypothesis has challenged the classical model and suggests that speech acoustic processing in auditory cortex occur based on the rate of a component that is inherent in speech signal [63]. According to the results, slow non-speech acoustic stimulations (3−5 Hz) lateralize in the right hemisphere auditory cortex [64] but rapid acoustic stimulations (20−50 Hz) lateralize in left hemisphere auditory areas [65]. Auditory cortex research in animals is indicative of potential mechanisms which make the basis of the dominance of right hemisphere for speech encoding. In different animal models, a large proportion of auditory cortex neurons show temporal envelope of species-specific sounds which have considerable structural similarities with

human sounds. These neurons are called tracking neurons (envelope peak). A possible explanation for non-symmetry of the phase locked to envelope phase locking is that a large number of tracking envelope peak exist in auditory cortex of the right hemisphere. Auditory cortex of the right hemisphere is dominant for encoding slow temporal features in speech, known as speech envelope, which shows syllabus patterns and is considered critically important for normal speech perception. According to the results, right hemisphere plays an important role in speech perception and this hypothesis supports that acoustic processing of speech includes signal decomposition to temporal components by rate-specialized neurons in auditory cortex of right and left hemisphere [59]. On the other hand, it is reported that those with damaged right hemisphere cannot discriminate between explicit and implicit meanings and are unable to perceive explicit emotional connotation of the words [66]. These findings reveal the significance of the right hemisphere in speech perception.

Applying positron emission tomography (PET), it was found that both speech statements and melodic statements result in activation of almost similar functional areas. These areas include primary motor cortex, supplementary motor area, Broca area, anterior insula, primary and secondary auditory cortices, temporal pole, basal ganglia, ventral thalamus, and posterior cerebellum. Some differences have been detected in lateralization because language tasks are mostly inclined to the left hemisphere but most activation is bilateral which creates a considerable overlap in various cases [67]. Further studies show that the exposure of left frontal lobe to transactional magnetic stimulation distorts speech but not melody. Therefore, different areas in the brain are involved in processing speech and melody. To offer a reason for such difference, researchers suggest that speech production can be localized well but basic mechanisms of melody production cannot [68].

It was revealed that musicians are equipped with a well-organized thalamotical network after long-term music training. Thalamotical-cortical network can modulate sensitivity to afferent information and modifies multi-modal information integration required for musical performance. Not only does the restructured thalamotical-cortical network of musicians contribute to higher sensitivity to sound, but it also contributes to the integration of mental image with sound and it is supposed that both functions are prominent in musicians [69]. It was as well demonstrated that cortico-thalamocortical network modifies higher-order functions such as language processing and memory retrieval. MRI examinations have proved structural connections between Broca's area and thalamus and it is stated that cortico-thalamocortical network selectively engages some cortical areas to save multi-modal lexical items to connect them together through lexical-semantic processing. This research has shown transfer and modification of information between Brodmann 44 and 45 [70]. The cortico-thalamocortical network is also involved in memory functions and damages in thalamus results in diencephalic seizure and anterograde episodic memory degradation [71].

Some studies conclude that structural differences due to music training extends beyond sensory cortices and reach the inferior frontal gyrus of the frontal lobe [72]. For instance, some researchers have reported shrinkage of bilateral dorsolateral prefrontal cortex and density of grey matter in the left inferior frontal gyrus in non-musicians due to aging. Therefore, music creates a protective shield for an individual up to the end of life [73].

Applying diffusion tensor MRI (DT-MRI) techniques, structural differences of white matter among musicians and non-musicians were examined. Generally, it was found that music training induces some changes in cross-hemisphere connections and generates significant differences in different areas of the corpus of musicians in comparison with non-musicians [74]. It was also found that musicians who received early training enjoy more connections in posterior midbody/isthmus of the corpus callosum and fraction anisotropy. Researchers conclude that training prior to the age of 7 changes the connections of white matter [75].

In a further study, the difference in the structure of grey matter of ventral premotor cortex (vPMC) was discerned between the two groups, i.e. those who received early music training and those who had late training. This difference is correlated with the age when the music training starts and the area of cortex in vPMC in musicians extends following early training. In other words, auditory-motor interactivity required for music practice contributes to plasticity in vPMC [76]. It seems that practicing music is a multimodal activity that leads to structural plasticity in the auditory area, motor area, and many other areas of the brain.

Function

There is a wealth of empirical evidence indicative of exchanges between music and language ranging from sensory-perceptual to cognitive domain [77]. It was found that musicians perform better than non-musicians in a wide range of auditory perception tests. This advantage may be due to the better processing of acoustic features such as pitch or F0 which makes the first step in music [78]. As the F0 and voice tract length (VTL) of the target speech voice and the envelope speech voice change, it is revealed that musicians resort less to VTL for better perception of the voice. Therefore, musicians surpass non-musicians in perceiving F0 and show better progress in speech perception ability when the F0 of sounds are different [79]. Better stream segregation in musicians may also be a reason [80]. On the other hand, this superiority can be due to better cognitive capabilities such as better attention or better working memory in auditory tasks [81].

Optimization of the auditory system results in better acoustic resolution in responding to different components of music, including pitch, duration, rhythm, timbre, and melody and different aspects of speech processing such as active [82] and passive [83] discrimination. Music training facilitates the processing of speech segmental and super-segmental cues of different temporal and spectral features, including VOT, latency [84], pitch [52], timbre [84], and the linguistic and emotional [85] prosody. Besides, music training is proved to contribute to speech categorical perception [86] and accelerate learning similar words, the spectral features of which are manipulated [87].

An important aspect of speech processing in daily auditory experience is the ability to perceive speech in acoustically unfavorable conditions. This problem mainly bothers those who suffer from hearing loss. For example, in a noisy party, one has to discriminate friends' voices against a multi-talker background so as to understand what is being narrated. Musicians perform better in segregating simultaneous sounds [88], which demands higher pitch discrimination ability [89], working memory [90], and selective attention [12]. As a matter of fact, when speech perception abilities of musicians and non-musicians, who are the same in terms of the auditory condition, are compared, better performance of musicians in noisy backgrounds is evident. According to the results of hearing in noise test (HINT), Quick-speech in noise (Q-SIN), frequency discrimination test, and working memory tests, musicians excel non-musicians in all tasks. Besides, the performance of musicians in all tests except HINT correlated with the number of years one practiced music. These findings show that in a multi-talker environment (Q-SIN) in comparison with environmental sound in the background (HINT), higher ability in frequency discrimination, selective attention, and working memory as a function of music specialty is significant [16]. Regarding speech perception, researchers found that musicians show better speech perception. They also found a correlation is found in items that improve through music training (i.e. better pitch perception or stream segregation) [21]. Fig. 2 represents the positive impact of music on basic, cognitive, and speech processing. Music training, by a focus on rhythm, is used as a rehabilitating tool for dyslexic children [91]. In a study carried out on three patients suffering from stroke and dyslexia in Broca's area, the proportional impact of rhythm and pitch on the effectiveness of melodic intonation therapy (MIT) was assessed. This kind of therapy is a song-based structured rehabilitation protocol for

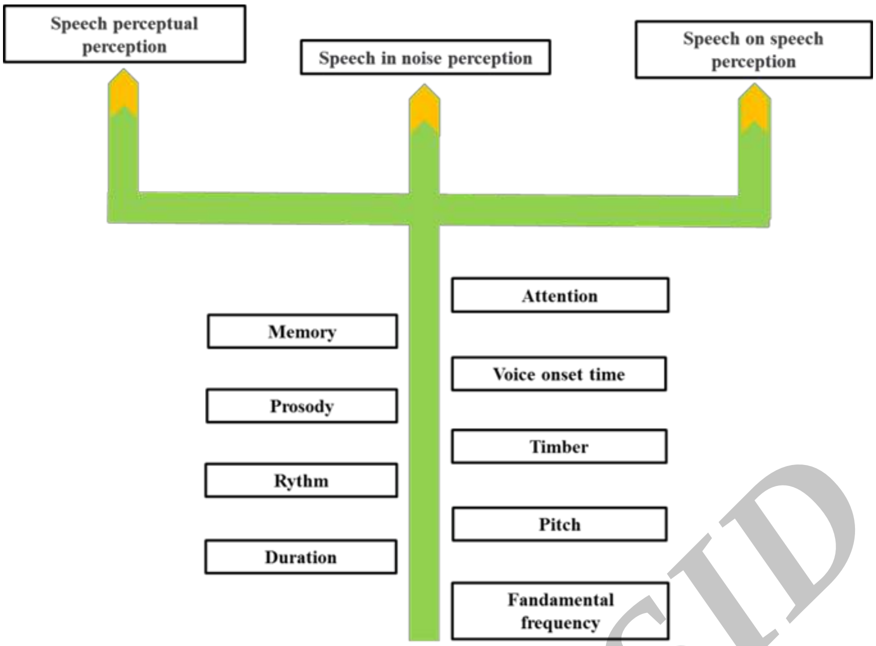

Fig. 2. The effect of music on fundamental processing, cognitive and speech.

dyslexic individuals. The participants were compared with regard to post melodic intonation therapy (using pitch and rhythm), rhythmic melodic therapy (using rhythm), and conventional speech therapy. Results showed that despite accuracy in stating all instructed sentences that improved following all kinds of therapies, melodic intonation therapy had the biggest effect regarding the uninstructed sentences and continuous speech. This result proves the significance of pitch and rhythm in training [92].

Researchers investigated the role of different components of MIT and its underlying mechanisms. They discovered four mechanisms which make MIT efficient: language function neuroplastic reorganization, integrating the system of mirror neurons and multi-modal integration, taking advantage of common points of music and language, and motivation and mood. These mechanisms represent the neurobiological, cognitive, and emotional effects of MIT which totally make therapy efficient. Sound Envelope Processing (SEP) synchronization and entrainment to a pulse hypothesis was developed for further investigation of rhythm impact on speech perception and production. According to this hypothesis, sound envelope processing, synchronization, and entertainment to pulse stimulate different brain networks, including auditory afferents, prefrontal-subcortical, striato-thalamocortical, and cortex motor efferent cycle [92].

Behavioral results of musicians are approved by electrophysiologic findings, too [16]. The morphology of brainstem response was less influenced in musicians than non-musicians by background sound. They studied the latency and amplitude of V/A, auditory brainstem response (ABR) which is indicative of the onset of consonant-vowel /da/, and formant transition (/d/ to /a/) in musicians and non-musicians in quiet and multi-talker environments. Comparison of the results in noisy conditions versus quiet condition showed that the latency of ABR peaks was less and amplitude was better maintained in musicians compared with non-musicians. Researchers concluded that the degrading effect of noise upon neural processing can be limited through music training [93]. Fuller et al. suggested that the superiority of musicians was mainly due to better processing of primary acoustic cues, not cognitive factors. However, some researchers emphasized considering the general cognitive abilities and their correlation with IQ

[94].

Some researchers reported that superiority of musicians in discriminating native vowel is related to the functions of working and echoic memory (not the auditory one), so that during the initial auditory processing phases (N1/P2 complex), no difference was detected between the two groups but different responses in N400 and P600 was achieved that shows faster learning is earned with optimizing recalling functions (not perceptual functions). Results demonstrate the relationship between mechanisms of learning faster in musicians and optimization of working memory (P600) and echoic memory (N400) [37]. In other words, some researchers believe in the effectiveness of music on cognitive mechanisms.

Conclusion

Recognizing the impact of music training on important aspects of human's cognition provides a thorough description of brain function and neural plasticity. According to the results, listening to music and music training leads to plasticity in auditory processing networks from cochlea to the auditory and non-auditory cortex. Studies show the importance of both bottom-up and top-down processing in this plasticity. Music training is related to sensory-perceptual advantages in different kinds of language abilities, including the processing of fundamental frequency, segmental, and super-segmental cues, voice onset time, duration, pitch, timbre, prosody, improved speech perception, degraded speech perception, speech on speech perception, speech in noise perception, and at cognitive level, the improvement in executive processing such as improvement of verbal memory, intelligence, working memory, and echoic memory. The superiority of musicians in speech perception may not be the direct result of better pitch perception but mostly because of other factors of auditory perception such as better stream segregation, better rhythm perception, or even better auditory-cognitive abilities. In other words, better attention of musicians to sound features can shape their selective attention mechanisms too and improves their analysis skills. In general, better selective attention and other top-down mechanisms which result from music training lead to simultaneous sound segregation which is an essential process for perceiving speech in noisy environments. This is especially of high importance in those who suffer from hearing loss. Findings of the present study pave the way for further studies in future for investigating the neurophysiological impacts of listening to music and music training upon speech perception of special populations, including those who suffer from hearing loss. Furthermore, they can be helpful in designing auditory education programs and preventive strategies for those who suffer from hearing loss.

Conflict of interest

The authors declared no conflicts of interest.

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