Advanced Review

Music perception and cognition: development, neural basis, and rehabilitative use of music

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Music is a highly versatile form of art and communication that has been an essential part of human society since its early days. Neuroimaging studies indicate that music is a powerful stimulus also for the human brain, engaging not just the auditory cortex but also a vast, bilateral network of temporal, frontal, parietal, cerebellar, and limbic brain areas that govern auditory perception, syntactic and semantic processing, attention and memory, emotion and mood control, and motor skills. Studies of amusia, a severe form of musical impairment, highlight the right temporal and frontal cortices as the core neural substrates for adequate perception and production of music. Many of the basic auditory and musical skills, such as pitch and timbre perception, start developing already *in utero*, and babies are born with a natural preference for music and singing. Music has many important roles and functions throughout life, ranging from emotional self-regulation, mood enhancement, and identity formation to promoting the development of verbal, motor, cognitive, and social skills and maintaining their healthy functioning in old age. Music is also used clinically as a part of treatment in many illnesses, which involve affective, attention, memory, communication, or motor deficits. Although more research is still needed, current evidence suggests that music-based rehabilitation can be effective in many developmental, psychiatric, and neurological disorders, such as autism, depression, schizophrenia, and stroke, as well as in many chronic somatic illnesses that cause pain and anxiety.

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INTRODUCTION

As the French poet Victor Hugo (1802–1885) put it, 'music expresses that which cannot be said and on which it is impossible to be silent'. Just like spoken language, music has been an essential part of every known human culture and therefore has roots that reach deep into our very selves and into our brains. Thus far, the oldest concrete evidence regarding the early existence of music was obtained a few years ago from southern Germany, where archaeological excavations revealed a 40,000-year-old flute made of bone.[1] Some scholars believe that a singing-based form of communication, a protolanguage, could be even older, possibly dating back over 200,000 years, and could have formed a basis for the development of modern spoken language.[2] More recently, various cultural trends and technological innovations, such as the karaoke and the choir singing boom, MP3 players, and digital streaming services and players (e.g., Spotify and iTunes), have made music more available and easily accessible than ever before. In its many forms, music has become a popular leisure activity and hobby through which many of us mediate our emotional and arousal state, experience creativity

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and aesthetic pleasure, and interact with others. Thanks to modern brain imaging methods, such as electroencephalography, magnetoencephalography (MEG), functional magnetic resonance imaging (fMRI), and positron emission tomography (PET), and behavioral and clinical studies, we are now starting to better understand how music affects us and how it can be used to promote well-being and facilitate recovery and rehabilitation. In this article, we aim to provide a brief review of the neural basis of music in both the healthy and the damaged brain, the development of musical skills and the meaning of music in different ages, and the effectiveness of music-based interventions in various somatic, psychiatric, and neurological illnesses.

NEURAL BASIS OF MUSIC

Music Processing in the Healthy Brain

Neuroscience of music is a relatively new, fast-developing field of science, which has during the past 20 years provided a lot of novel information on how music is processed in the brain, how musical activities can shape the brain, and what neural mechanisms underlie the therapeutic effect of music. To date, converging evidence suggests that music activates an extremely complex and wide-spread, bilateral network of cortical and subcortical areas that control many auditory, cognitive, sensory-motor, and emotional functions (see Figure 1).

The processing of music begins in the inner ears where acoustic information is converted to an electric impulse or signal. The signal then travels along the auditory nerve to the brain stem (especially to the inferior colliculus) where certain basic features of the sound, such as periodicity and intensity, are first processed. Interestingly, the earliest signs of musical training can be seen as immediately as 10 milliseconds after sound onset in the auditory brain stem, which in musicians can represent the frequency of the sound with more fidelity than in nonmusicians.[3] From the brain stem, the auditory information is conveyed to the thalamus and from there primarily to the auditory cortex (AC), but also directly to limbic areas, such as the amygdala and the medial orbitofrontal cortex.[4] The primary AC and its neighboring superior temporal areas analyze the basic acoustic cues of the sound, including frequency, pitch, sound level, temporal variation, motion, and spatial location.[5] The left AC has a better temporal resolution and the right AC has a better spectral resolution, which is thought to form one crucial premise for the lateralization of

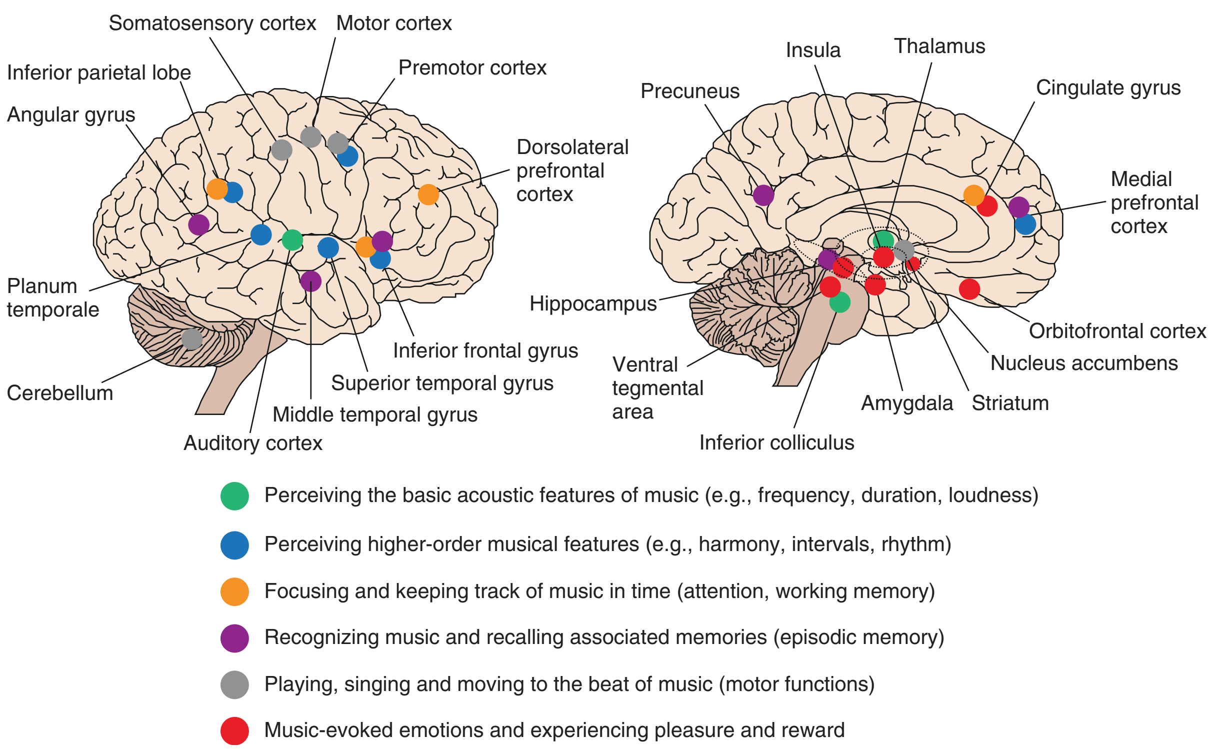

FIGURE 1 | Schematic illustration of key brain areas associated with music processing-based neuroimaging studies of healthy subjects. Note that although the image displays the lateral and medial parts of the right hemisphere, many musical subfunctions are actually largely bilateral (with the exception of pitch and melody processing, which is more lateralized to the right hemisphere).

speech to the left hemisphere and music to the right hemisphere.[6]

Music is, however, much more than just the sum of its basic acoustic features. Upon its initial encoding and perception, music triggers a sequence of cognitive, motor, and emotional processes in the brain that are governed by numerous cortical and subcortical areas. Next, we outline five such processes.

1. The perception of higher order musical features, such as chords, harmonies, intervals, and rhythms, calls for a rule-based syntactic analysis of complex patterns of spectral and temporal fluctuations within the sound stream. According to neuroimaging studies, this takes place in a network comprising the inferior and medial prefrontal cortex, the premotor cortex, the anterior and posterior parts of the superior temporal gyrus, and the inferior parietal lobe.[7,8]
2. Continually keeping track of the music, which always unfolds over time, requires the engagement of the attention and working memory system, which is spread over many prefrontal areas (especially the dorsolateral prefrontal cortex), the cingulate cortex, and inferior parietal areas.[9,10]
3. Hearing music that is familiar to the listener from past experience triggers processing especially in the hippocampus as well as in medial temporal and parietal areas, which are involved in episodic memory.[11,12]
4. Hearing music that touches us emotionally engages a network of many deep limbic and paralimbic areas, including various midbrain areas, striatal areas (especially nucleus accumbens), the amygdala, the hippocampus, the cingulate cortex, and the orbitofrontal cortex.[13,14] This dopaminergic network is known as the mesolimbic or reward system of the brain and it has been implicated in the experiencing of emotions, pleasure, and reward and in regulating the autonomic nervous system (ANS) and the endocrine (or hormone) system. Recently, the direct involvement of striatal dopamine in the emotional reaction to music was demonstrated in a combined psychophysiological, PET and fMRI study.[15]
5. Perceiving the rhythm of music, moving to the beat of music, or producing music (by singing or playing an instrument) involves the sensory-motor networks of the brain, including areas in the cerebellum, the basal ganglia, and the motor and somatosensory cortices.[16,17]

Music Processing in the Damaged or Abnormal Brain: Amusia

Our ability to perceive, process, and appreciate music may become impaired in many neurological illnesses. The most well-known disorder is amusia, which can be either innate (congenital amusia) or result from a brain lesion (acquired amusia). The term amusia refers to an inability to perceive and/or produce music, which is not caused by a disorder in another domain, such as hearing, motor, or cognitive functions.[18,19] Amusia can be observed in the majority of musical features (perceiving pitch, timbre, or rhythm or recognizing musical emotions or musical pieces) or be specific to one or some of them. The most commonly reported deficit is that of poor pitch discrimination: amusic individuals are typically not able to perceive pitch changes smaller than a semitone.[20] As a result, they often have great difficulties in perceiving sequential notes (or tones) and, therefore, in recognizing melodies—for some rare individuals, music may sound more like noise.

It has been estimated that the prevalence of congenital amusia is approximately 2–4% in the general population.[21] Genetic studies of congenital amusia suggest that the disorder is heritable: in amusic families, 39% of first-degree relatives have the same deficit, whereas only 3% have it in the control families.[22] Furthermore, dizygotic (identical) twins have more uniform performance in a musical pitch perception test than monozygotic (fraternal) twins.[23] Compared to congenital amusia, acquired amusia seems to be a lot more common deficit, at least after a cerebrovascular accident such as stroke. In studies of stroke patients, the reported incidence of amusia is 60% in the acute stage (about 1 week postonset) and around 40% in the subacute/chronic stage (>3 months postlesion).[24,25] On the basis of structural and functional MRI studies, the crucial neuroanatomical correlate of congenical amusia appears to be the superior temporal gyrus (AC) and the inferior frontal gyrus in the right hemisphere as well as the subcortical white matter tracts (arquate fasciculus) connecting these areas.[26–28] Correspondingly, acquired amusia is most typically caused by damage to the AC and its surrounding cortical and subcortical areas (anterior and posterior superior temporal gyrus and insula) or to temporoparietal or inferior frontal areas, especially in the right hemisphere[19] (see Figure 2).

Interestingly, amusia can occur independently of or in parallel with linguistic disorders, thereby raising an intriguing question of whether the neural mechanisms of music and speech processing are separate or shared. In studies of brain-damaged patients, approximately half of the patients with

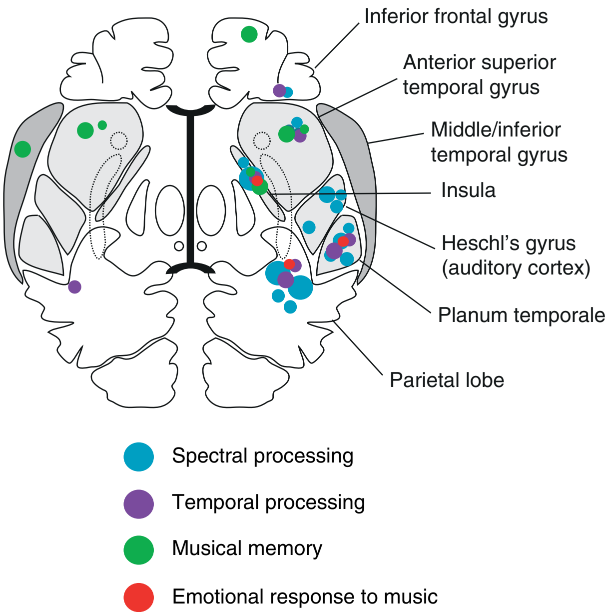

FIGURE 2 | Critical brain areas where damage typically leads to an amusic deficit in spectral processing (perception of pitch intervals or patterns, tonal structure, and timbre), temporal processing (perception of time intervals and rhythm), musical memory (recognition of familiar or novel musical material), or emotional response to music. The size of each circle is scaled to the proportion of studies of the function implicating that region. (Reprinted with permission from Ref 19. Copyright 2006 Oxford University Press)

acquired amusia have been documented to have at least minor aphasia,[19] although there are also cases of clear double dissociations (amusia without aphasia and vice versa), suggesting that there may be separate neural modules for music and speech.[29] Recent studies, however, have found that aphasic patients also have difficulties in perceiving musical structures[30] and, conversely, that individuals with congenital amusia have difficulties in perceiving the intonation and prosody of speech,[31] thereby supporting the alternative view that there are commonalities between speech and music perception at the neural level.

DEVELOPMENT AND UTILITY OF MUSIC ACROSS LIFE SPAN

Music, especially hearing singing and producing musical sounds, appears to evoke the natural interest of infants and children across cultures.[32] Indeed, babies seem to be born with innate musical abilities: even small infants can detect the pitch, timbre, and duration of the sounds, recognize familiar melodic and rhythmic patterns, and prefer consonant over dissonant music and singing over speech.[32] Infants are also sensitive to prosody, in other words, to changes in the melody, rhythm, stress, and intonation of speech, which are used to communicate emotions and to emphasize word meanings in speech. Intuitively, parents tend to speak to their babies in a manner which utilizes this sensitivity. In fact, infant-directed speech (or motherese) contains many musical or singing-like elements, such as strong pitch fluctuations and repetitive melodic line, which help the infant to grasp and acquire the essential structure of natural speech.[33] Lullabies and play songs are also globally used to modulate the arousal level of infants, as reflected, for example, in salivary cortisol changes.[33] At the age of 6 months, babies start to babble and to 'dance', i.e., to adjust their movements with the tempo of music.[34] For a toddler, musical activity is a playground of sorts, where parents can use reciprocal communication and rhythmic movements to regulate the emotional and attentional state of the child. At the same time, the child him/herself can practice the cognitive, motor, and social skills needed for speech acquisition and communication.

At preschool age, children are often enthusiastic in expressing music with their gestures and movements and in taking part in musical activities as listeners, singers, players, and dancers. In many native cultures, music making or dancing is an integral and natural part of the everyday life of children. For the developing brain, repeated exposure to music in the growing environment can be beneficial. In developmental animal studies, an enriched auditory environment that contains complex sounds or music has been shown to improve auditory functions, learning, and memory as well as induce neural plasticity, as indicated by changes in neurotransmitter (e.g., dopamine and glutamate) and neurotrophin (e.g., brain-derived neurotrophic factor) levels, synaptic plasticity, and neurogenesis.[35,36] According to studies on children, musical hobbies can improve auditory and motor skills as well as high-level cognitive skills such as logical reasoning, executive functioning, attention, and memory.[37–39] Musical skills and music training seem to be also related to speech perception and pronunciation of foreign language.[40,41] At the neural level, structural changes in the primary AC, the primary motor cortex, and the corpus callosum have been observed already after 15 months of individual piano lessons.[37]

During adolescence, music serves as a forum for constructing the developing self-identity, forming interpersonal relationships, and experiencing agency and self-control, and in dealing with negative emotions and stress.[42] Furthermore, a key aspect of all musical activity is emotional expression, which, according to a recent theory,[43] is at least partly mediated by the mirror neuron system, a set of frontal and parietal cortical structures thought to contribute to understanding the actions of other people (i.e., empathy), learning new skills by imitation, and to theory of mind and which continue to develop through adolescence and early adulthood. Musical activity, or even simple music listening, can thus form a safe shared and dynamic platform for exploring one's emotional processes with respect to others and for forging relationships through common experiences, chats, and discussions. Some evolutionary theories of music postulate that joint musical activities, such as singing and dancing with others, facilitate the release of endorphins and the experience of reward and pleasure, which in turn promote group cohesion and social bonding.[44]

Finally, music has a lot to give also in adulthood and in old age. In most cases, individual musical preferences are formed during adolescence and early adulthood—maybe because of this, music also offers means to refresh and process memories and reflect on prior experiences later in life. During adulthood, music is strongly linked to emotional and self-conceptual processing, mood, and memories.[45] Music continues to play a vital role as well during aging. Studies suggest that regular musical activities are very important to seniors in maintaining psychological well-being and in contributing to positive aging by providing ways to maintain self-esteem, competence, and independence and in reducing loneliness and isolation.[46]

THERAPEUTIC AND REHABILITATIVE USE OF MUSIC

Broadly defined, music therapy is an intervention provided by a trained music therapist where music is used in a therapeutic interaction with the client to achieve individually defined goals. The methods utilized in music therapy include, for example, music listening, singing, instrument playing, musical improvisation, and song writing. In contrast, musical interventions that are provided by other nursing or rehabilitation staff (typically music listening) are usually referred to as music medicine. Although both music therapy and music medicine utilize music as a therapeutic tool, the key difference between them is the involvement of a trained music therapist and the therapeutic relationship between the therapist and the client, which are important contributors in the efficacy of music therapy. However, for simplicity, both music therapy and music medicine are referred to hereafter as music interventions. The scientific study of the efficacy of different music interventions has increased rapidly during the past 20 years, and the experimental evidence for these interventions is accumulating regarding their clinical utility and applicability in the treatment and rehabilitation of many somatic, psychiatric, and neurological illnesses. On the basis of Cochrane Reviews published so far (www.cochrane.org), there are currently about 160 published music intervention studies (involving a total of over 9000 patients) that meet the strict methodological criteria of a randomized controlled trial (RCT). In the following sections, we will briefly review what is currently known about the efficacy of music interventions regarding five domains: emotion, attention and sensory functions, memory, communication, and motor functions.

Emotion

Perhaps more than any other sensory stimulus, music is capable of evoking a wide spectrum of deep and powerful emotions, including, for example, joy, serenity, sadness, and nostalgia. The transient emotional effect of music is manifested not just as a subjectively experienced feeling or emotional state but also as a physiological change, for example, in heart rate, respiration, skin temperature and conductance, and hormone (e.g., cortisol, oxytocin, and β-endorphin) secretion,[47] indicating an impact on the ANS or endocrine system as well as the activity of the aforementioned limbic/paralimbic brain areas.[13–15] Consequently, music interventions have often been applied to the rehabilitation of persons suffering from various affective disorders, such as depression and anxiety, or from illnesses with more severe neuropsychiatric symptoms, such as schizophrenia or Alzheimer's disease (AD).

In the field of depression, a recent meta-analysis of five RCTs ($n = 237$) found that music therapy is an applicable method that can improve depressed mood, although more high-quality trials are still needed to draw more firm clinical conclusions.[48] Also, another meta-analysis, which included RCTs and other controlled studies of patients ($n = 319$) with various severe mental disorders, found that music therapy had a significant positive effect on depression and anxiety symptoms of the patients.[49] One new and promising therapeutic technique for treating depression is improvisational psychodynamic music therapy, which was recently shown to reduce depression and anxiety symptoms and improve general functioning in working-age depressed patients.[50] In patients diagnosed with schizophrenia or schizophrenia-like disorder, a recent meta-analysis of eight studies ($n = 483$) came to a conclusion that music therapy can help to improve the global and mental state and the social functioning of the patients and to reduce their negative symptoms, depression, and anxiety, if provided in sufficient quantity.[51]

Regarding AD and other forms of dementia, an updated Cochrane review of 10 studies ($n = 396$) reported that music therapy may be effective in reducing neuropsychiatric and behavioral symptoms, such as agitation and wandering, as well as in enhancing social and emotional functioning.[52] However, the authors also cautioned that the methodological variability between the studies precludes making any robust conclusions about the clinical utility of music therapy and more high-quality studies are still called for. Finally, another line of meta-analytical evidence suggests that music interventions can be effective in reducing anxiety, improving mood, and influencing ANS parameters (heart rate, respiration, and blood pressure) also in patients suffering from severe chronic somatic illnesses, including cancer (30 RCTs, $n = 1891$)[53] and coronary heart disease (23 RCTs, $n = 1461$).[54]

Attention and Sensory Functions

One attribute that is also quite unique to music is the capacity to draw and direct attention and influence arousal and vigilance. Clinically, this attribute has been effectively utilized in the alleviation of pain, which remains as one of the most studied therapeutic applications of music.[55] A comprehensive meta-analysis (51 RCTs, $n = 3663$), which evaluated the effect of music interventions compared to controls on various types of pain (e.g., acute pain, chronic pain, neuropathic pain, cancer pain, and postsurgical pain), indicated that music is able to reduce the level of subjectively experienced pain intensity and also to reduce the amount of opioids required to manage the pain, especially in the case of postsurgical pain.[56] Again, however, the effects were quite modest according to the authors, and the clinical importance still remains unclear. In future, the analgesic use of music could be a viable option especially for children and adolescents with whom there are less systematic studies of the suitable dosage and the potential side effects of painkillers.[55] In neonatal units, music is increasingly used to improve the behavioral or physiological outcomes of preterm infants, and currently there is preliminary evidence that music, especially maternal singing, may reduce pain and improve sucking and weight gain in preterm infants.[57,58]

Another interesting and novel application of music is the treatment of tinnitus. Tinnitus, the unpleasant and recurrent perception of a sound, often a ringing or a buzzing one, in the absence of corresponding external sound, is most often caused by noise-induced hearing loss or various illnesses, and ultimately results in maladaptive plastic changes in the AC. The contemporary view on tinnitus biology holds that although tinnitus may be triggered by injury to the inner ear, the neural generators are most readily found centrally in the brain. On the basis of an idea of music-induced neuroplasticity and lateral inhibition in the human AC, Pantev and coworkers have recently developed a novel treatment strategy for tonal tinnitus called tailor-made notched music training (TMNMT). By notching the music energy spectrum around the individual tinnitus frequency, the idea of TMNMT is to attract lateral inhibition to auditory neurons involved in tinnitus perception. The results of a 12-month controlled follow-up study ($n = 39$) found that subjective tinnitus loudness and annoyance were significantly reduced after TMNMT but not in a placebo group where the notching spared the tinnitus frequencies.[59] Correspondingly, MEG results also showed that tinnitus-related auditory evoked fields were significantly reduced after the TMNMT training.[59] Given that tinnitus is highly prevalent (10–15%) in the adult population, can lead to severe depression and even suicide, and currently lacks effective drug treatment, these results are highly important and promising.

A third example of the attention-influencing effect of music is attention-deficit/hyperactivity disorder (ADHD). Abikoff et al.[60] performed a study where 20 ADHD children and 20 healthy control children worked on an arithmetic task while being exposed to their favorite music, to background speech (news report), and to silence. The performance of the control children did not differ between the three conditions, whereas the ADHD children performed significantly better in the music condition than in the speech and silence conditions, especially if the music condition was the first.[60] In addition to ADHD, music may have an attention-stimulating effect also on stroke patients suffering from unilateral spatial neglect (USN), a deficit in awareness for information presented on the side of space that is contralateral to the site of the brain lesion (e.g., impaired awareness of the left side following a right hemisphere lesions). In one study, 14 USN patients were given tactile, auditory verbal, or auditory nonverbal (white noise or classical music) stimulation or no stimulation while performing a visuospatial copying task.[61] Only nonverbal auditory stimuli were found to decrease neglect on the task.[61] In another study of three USN patients, especially music that was emotionally pleasant to the patient was found to ameliorate neglect in a visual awareness task and also induce functional coupling between the emotional and visual attentional brain areas in the right hemisphere.[62] In summary, music seems to be effective, at least temporarily, in modifying the orientation and maintenance of attention in persons suffering from a neurological disorder, suggesting that it could potentially be utilized in their education and rehabilitation.

Memory

Hearing and perceiving music naturally entail keeping track of the incoming auditory information as the music unfolds in time, analyzing the structure and meaning of the music, and identifying the music and retrieving the experiences and memories that are associated with it. In the brain, all this recruits areas associated with auditory sensory memory, working memory, and episodic and semantic memory. By affecting our mood and arousal state, music can also temporarily improve cognitive performance, including memory performance,[63] although this effect is still somewhat controversial.[64] However, there is some evidence suggesting that this may also occur in persons with dementia. Irish et al.[65] tested the autobiographical recall of 10 AD individuals and 10 control subjects under two conditions, music (exposure to Vivaldi's 'Spring') and silence, and found that the performance of the AD individuals improved considerably in the music condition. Similarly, in another study, 29 elderly persons with mild or moderate dementia answered autobiographical memory questions from three life eras (remote, medium-remote, and recent) while being exposed to familiar music, novel music, cafeteria noise, or quiet.[66] Recall was significantly better in music than in noise or quiet, especially regarding remote experiences.[66] Interestingly, music may also function as a mnemonic aid in AD. In a recent study, 13 AD individuals and 14 healthy older controls were presented with printed lyrics of unfamiliar children's songs accompanied by either spoken or sung versions of the songs.[67] AD individuals had better recognition accuracy for the sung lyrics than the spoken lyrics, whereas the healthy controls showed no significant differences.[67]

Taken together, these results suggest that music may have a small short-term facilitating effect on memory performance in dementia, but currently the data are still insufficient to draw firm conclusions about the clinical efficacy of music in dementia, especially regarding its long-term cognitive effect.[68,69] In contrast, studies of healthy seniors have found that regular musical activities, such as playing an instrument, can improve cognitive functioning, for example, in tasks of attention and executive functioning.[70] In a longitudinal study of 469 subjects older than 75 years, frequent reading, playing board games, playing musical instruments, and dancing were found to be the leisure activities that were most associated with a lower risk of developing dementia later.[71] Also, in a recent randomized longitudinal study of elderly stroke patients ($n = 55$), daily music listening was found to have a positive effect on the recovery of verbal memory and focused attention compared with patients who listened daily to audio books or received only standard care.[72] The positive effects on memory were also coupled with reduced depression and confusion during the early recovery stage,[73] suggesting that the positive effect of music on cognition is at least partly mediated by enhanced mood.

Communication

Both music and speech are forms of communication that make use of the acoustic properties of sound, such as pitch, timbre, and rhythm. This link is evident also in studies of musical training, which have shown that musical training can enhance the processing of the acoustic features of speech and also facilitate language skills, such as reading, speech segmentation, and perceiving speech in noise.[3,41] According to the recent OPERA hypothesis,[74] these beneficial effects may be related to the fact that the brain networks processing the acoustic features of music and speech *overlap* anatomically; that music places higher demands on the *precision* of processing in these shared networks than speech; and that the musical activities, which engage this network, typically elicit strong positive *emotions*, are frequently *repeated*, and require focused *attention*. Clinically, music has been utilized in training communication skills in various patient groups.

One clinical population who often lacks proper communication skills but in many cases has enhanced auditory and musical abilities, such as superior pitch processing, are children with an autistic spectrum disorder (ASD). Currently, some meta-analytical (three RCTs, $n = 24$) evidence exists that music therapy may help ASD children to improve their communicative skills.[75] Music may be an especially important therapeutic tool for those ASD children who are nonverbal. Recently, a novel intervention called auditory-motor mapping training (AMMT) has been developed, which aims to promote speech production by training the association between sounds and articulatory actions using intonation and bimanual motor activities. In a small pilot study, six ASD children who had no intelligible speech were given frequent sessions of AMMT and were all found to improve in their ability to articulate words and phrases, with generalization also to nonpracticed items.[76]

Another example of a music-based rehabilitation method that emphasizes the melodic and rhythmic elements of speech is melodic intonation therapy (MIT), which has been developed to train speech production in aphasic patients. The core idea of MIT is to lead nonfluent aphasic patients from singing simple, 2-3 syllable phrases to speaking longer phrases by utilizing melodic intonation (intoning syllables on different pitches), inner rehearsal (covert production of the phrase), and rhythmic motor sequencing (tapping with the functioning left hand once per syllable). Although the efficacy of MIT has yet to be substantiated in an RCT, evidence from small case series suggests that an intense course of MIT can lead to improvement in spontaneous language skills.[77] Pilot fMRI and diffusion tensor imaging data indicate that the verbal improvement may be related to functional and structural neuroplastic changes in the spared right frontotemporal network.[77]

Motor Functions

Rhythm and movement are intimately connected to music. In fact, some cultures do not even differentiate 'music' and 'dance' in their vocabulary. Also in the human brain, almost all musical activity, even the passive listening of music, automatically recruits motor areas, and there is rich connectivity between auditory and motor brain areas.[17] Clinically, our innate tendency to sequence and entrain movements to the beat of music has been utilized in the rehabilitation of walking in many neurological illnesses, including stroke, traumatic brain injury, and Parkinson's disease (PD). One method has proved to be especially useful in this respect: rhythmic auditory stimulation (RAS). In RAS, an external auditory rhythm is provided by a metronome or by specifically prepared music tapes and adapted to the gait cadence of the patient—the idea is that auditory rhythms entrain motor rhythms via the close neural connections between the auditory and motor areas. A recent meta-analysis of studies of music therapy in acquired brain injury patients (seven RCTs, $n = 184$) concluded that RAS may be beneficial for improving gait parameters in stroke patients, including gait velocity, cadence, stride length, and gait symmetry.[78] Also in PD, there is evidence that patients are able to stabilize and synchronize their disturbed gait with the help of an external auditory rhythm[79,80] and that their motor coordination may be temporarily improved by familiar and stimulating music.[81]

Another way to use music in motor rehabilitation is to utilize active music making in the form of instrument playing. Recently, a method called music-supported therapy (MST) has been developed where fine and gross motor movements of the affected upper extremity are trained by playing progressively more difficult series of tones or simple melodies with a simplified MIDI-piano keyboard or electronic drum set. Studies of both subacute ($n = 77$) and chronic ($n = 20$) stroke patients found MST to be effective in improving both fine and gross motor skills with respect to the speed, precision, and smoothness of movements.[82,83] The fMRI results also suggest that MST may have a facilitating impact on the activity and functional connectivity of the auditory-motor networks in the temporal and frontal lobes that support musical perception and learning.[83]

CONCLUSION

In this article, we have reviewed a number of studies, which together shed light on the neural basis, development, and rehabilitative use of music. Modern neuroimaging has shown that musical activities, ranging from simple music listening to singing and playing a musical instrument, have diverse positive effects on the structure and function of the brain. Musical activities have different roles and meanings in different phases of life: during infancy and early childhood, they can support speech development; during school years, they can develop cognitive and attentional skills; during adolescence, they help to build self-identity and enhance emotional self-regulation; and during adulthood and old age, they help maintain cognitive performance and memory and improve mood. Clinically, the use of music therapy and other music interventions as a form of treatment and rehabilitation has received scientific support especially in somatic, psychiatric, and neurological illnesses involving deficits in emotions, attention and sensory functions, memory, communication, and motor functions. Currently, research in the fields of music therapy, psychology, and cognitive and affective neuroscience is beginning to merge, and now there are ongoing multidisciplinary studies in many countries aimed toward determining the clinical impact of music and uncovering its underlying neural mechanisms. In the future, especially large-scale and high-quality RCTs that combine both reliable and valid behavioral outcome measures and modern psychophysiological and neuroimaging measures would be optimal and highly valuable in this regard. Another topic, which is becoming more and more important with the recent development of portable music players and the increasing popularity of communal musical hobbies, is the long-term impact of self-directed musical leisure activities (such as music listening and choir singing) on health and well-being, especially in elderly persons. In summary, although the research field is still relatively young and more studies are still needed, music can be considered as a viable and promising nonpharmacological form of treatment and rehabilitation and, more generally, as an enriching and useful hobby that can shape the development and maintain the healthy functioning of the brain across life.

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