

# Neural Correlates of Musical Behaviors

## A Brief Overview

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**ABSTRACT:** Musical behaviors activate nearly every region of the brain that has so far been mapped. These neural structures are reviewed in a domain-specific overview to include the stimulus-response matrix for sensory activation, motor action planning, and cognitive and emotional reactions to music. Also reviewed are the effects of learning an instrument, similarities and differences in speech versus musical communication, and the potential health benefits of music. This review provides a framework and foundation for understanding the effects of music therapy and other interventions designed to improve the mental and physical health of children and adults.

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Much of what we know (or think we know) about the brain rests on an assumption called the *localization hypothesis*: the brain is not just a mass of undifferentiated tissue, but rather, specific neural regions underlie distinctive behaviors, thoughts, and actions. This is reflected in the names we give to brain regions, such as *motor cortex* (for movement), *sensory cortex* (for processing information from the five senses), *auditory cortex*, and *visual cortex*. Evidence for regional specialization comes from case studies of patients with lesions, and from various neuroimaging technologies (Positron Emission Tomography, or PET; functional Magnetic Resonance Imaging, or fMRI; Magnetoencephalography, or MEG; Electroencephalography, or EEG), as well as animal studies.

It is seductive to think of a one function—one brain mapping schema, whereby function  $x$  is handled specifically and exclusively by brain region  $y$  and so on. There may be some truth to this, but the situation is far more complex. The human brain is massively parallel and distributed. Although aspects of certain functions can be localized, other functions are likely to be distributed widely across different brain regions in functional circuits or networks. Lower level functions such as pitch perception are more likely to be localized to specific regions, whereas higher-level functions such as melody recognition are more likely to involve networks taking inputs from several widely dispersed regions. It is important to bear in mind these general principles when thinking about brain regions and musical activities.

This paper reviews neuromusical behaviors in three domains: (1) perceptual-cognitive, including the communicative functions of music and speech, (2) emotional reactions to

music, and (3) effects of music on immune function and health.

### Perceptual-Cognitive Processing of Music

Music consists of six fundamental attributes: pitch, duration, loudness, timbre, spatial location, and reverberant environment (Levitin, 2010). A set of two or more pitches gives rise to contour and melody, and a set of two or more durations gives rise to rhythm. Thus, melody and rhythm are secondary aspects of these fundamental attributes.

Unlike light, which is easily transmitted in a vacuum, sound requires a medium of transduction such as air or water. Pressure waves in the air (for example) stimulate the tympanic membrane (eardrum) and to some extent, the bones surrounding the ear; these pressure waves are turned into electrical signals that are transmitted to the brain. Sound can activate unconscious, reflex actions (mediated by the brain stem and pons), the most well-known of these being the startle reflex, which occurs before any conscious process alerts us of an impending danger.

One striking aspect of the brain's response to sound is that the neural response to sound is isomorphic to the sound itself. In other words, if we look at the waveform of a piece of music, and then at the waveform of the brain's response to that music, the two waveforms are nearly identical. This is true for single cell recordings in the inferior colliculus (Janata, 1997) or evoked potentials of the brainstem taken from the scalp (Skoe & Kraus, 2010). In fact, the output of such brain measures can be connected to a loudspeaker, and sounds approximating the music itself can be heard (Levitin, 2007). These findings provide evidence that pitch perception, one of the foundations of music, is innately wired into our brains.

Pitch is encoded at every level of the auditory system, beginning with the cochlea, inside of which exists a tonotopic (pitch by location) mapping. In other words, if we could uncoil the cochlea and flatten it out, we would see that its hair cells on one end are maximally responsive to low frequencies, hair cells on the other are maximally responsive to high frequencies, and intermediate regions are responsive to intermediate frequencies. In effect, the cochlea is laid out like a piano keyboard (but without the height differential between black keys and white keys!). This tonotopic mapping exists also in the inferior colliculus (Merzenich & Reid, 1974; Rose, Greenwood, Goldberg, & Hind, 1963; Ryan & Miller, 1978) and in the primary auditory cortex (Bendor & Wang, 2006; Talavage et al., 2004).

The pitch of musical sounds is processed in Heschl's gyrus bilaterally (Patterson, Uppenkamp, Johnsrude, & Griffiths, 2002). Posterior regions of secondary auditory cortex process pitch height (i.e. octave designation) and anterior regions process pitch *chroma* or pitch *class* (Tervaniemi & Huotilainen,

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nen, 2003; Warren Uppenkamp, Patterson, & Griffiths, 2003).<sup>1</sup> When two or more pitches combine to form intervals, contour and melody activation is seen in the superior temporal gyrus (STG) and planum polare (Patterson et al., 2002).

The neural mechanisms for perceiving rhythm are intimately bound with those for producing it, even in the absence of physical movement (Grahn & Rowe, 2009). Sensorimotor coordination is facilitated by music (Altenmüller, Wiesendanger, & Kesselring, 2006; Large, 2000), particularly music with a strong beat (Grahn & Rowe, 2009) and tempo has been shown to mediate involvement of motor areas in beat perception, specifically the premotor cortex, inferior frontal gyrus, superior temporal gyrus, and inferior parietal lobule (McAuley, Henry, & Tkach, 2012).

Musical activities activate the sensory and motor cortices. Playing an instrument activates muscle regions of the contralateral motor cortex and the tactile feel of strings, bows, keys, and other instrument surfaces activates the corresponding sensory representation in (contralateral) cortex. Dancing to music activates regions for movement and associated motor action plans in the premotor cortex, the basal ganglia, and the cerebellum (Mesulam, 1985). Synchronizing steps to music activates the cerebellar vermis, moving to a regular rhythm activates the right putamen, and spatial navigation of legs activates the medial superior parietal lobe (Brodmann Area 5/7 and the precuneus; Brown, Martinez, & Parsons, 2006).

Music also activates the *visual* cortex. The obvious case is when musicians read music and visual cortex processes information received from the retina. Less obvious is when we watch a live performance and use visual information to interpret the structural and emotional aspects of the performance. Indeed, even with the sound turned off, spectators watching a video of a musical performance understand a great deal of information about the structural and emotional qualities of a musical performance (Vines, Krumhansl, Wanderley, Dalca, & Levitin, 2011; Vines, Krumhansl, Wanderley, & Levitin, 2006), and these show distinct neurophysiological correlates (Chapados & Levitin, 2008).

One study found that when imagining a performance of music, the participant's visual memories of the performer's movements were reflected in visual cortical activity (Levitin, 2009). That same study also found that during the act of composing inside the scanner, the composer under study (Gordon Sumner, aka Sting) showed activation in regions of visual cortex which he subsequently explained was due to invoking metaphors of music-as-architecture and spatial arrangements when he writes: "My favorite music to listen to is probably Bach. And when I listen to Bach, I hear architecture—I really do—massive chambers and towers and buttresses and ever-increasing domes."

### **Bodily Movements in Music Performance and Perception**

All musical sounds begin with movement of some type—plucking, bowing, blowing, strumming, hitting, scraping, and so on (Levitin, McAdams, and Adams, 2002). Singing is

similar, involving the forcing of air through the vocal folds and motor movement of the vocal folds, tongue, and lips (Cook, 1999). Thus, music making and movement are intertwined. Listening to music may activate mirror neurons in the motor cortex (Rizzolatti, Fadiga, Gallese, & Fogassi, 1996) that cause us to think (at least unconsciously) about those motor movements that would be required to make the music. Movement learning may be subserved by these mirror neurons, and eventually this activation could lead to new learned behaviors.

When we move our bodies to music, there is neural activation in the premotor cortex, motor cortex, the cerebellum and basal ganglia (Levitin, 2007; Mesulam, 1985) and voluntary movements activate the precuneus as well, a region of the parietal lobe (Brown & Parsons, 2008). Tapping in synchrony to the pulse of a musical sequence (by humans) engages the presupplementary motor area, the supplemental motor area, the dorsal premotor cortex, the dorsolateral prefrontal cortex, the inferior parietal lobule, and lobule VI of the cerebellum, as measured by the blood oxygenation level dependent (BOLD) response (Chen, Penhune, & Zatorre, 2008).

When listening to music, many people report that it is difficult to avoid moving their bodies, whether it is a simple head nod to the beat, a body sway or a foot tap. This movement is processed via the medial geniculate nucleus, a subcortical auditory relay station (Brown & Parsons, 2008); the absence of communication to cortical structures following automatic, synchronous movement to music can therefore be interpreted as biologically and behaviorally unconscious (Levitin & Menon, 2003; Levitin et al., 2003). Even when lying perfectly still, listeners in fMRI studies show activation in those regions of the brain that would normally orchestrate motor movement to music, including the cerebellum, basal ganglia, and cortical motor areas—it is as though movement is impossible to suppress (Levitin, 2009; Levitin & Menon, 2003). Additional data implicate the dorsal premotor cortex (dPMC) in rhythmic synchronization. Participants tapped to rhythmic sequences of varying levels of metric difficulty; greater difficulty was correlated with increased dPMC activation (Chen et al., 2008).

An emerging body of literature links dance with therapeutic outcomes (Earhart, 2009). Music and movement together have also been found to be effective for children with severe and multiple disabilities (Meadows, 2002), and to improve attention in individuals with autism spectrum disorders (See, 2012). Intentional movements to music, and dancing in particular, are common across cultures and across the lifespan. Among young adults describing activities associated with music, one of the most common activities noted was dancing (Janata, Tomic, & Rakowsky, 2007). They may even be present across species, according to one study of a sulphur-crested cockatoo that dances to pop music (Patel, Iverson, Bregman, & Schulz, 2009).

The connection between auditory and kinesthetic senses was explored in a series of studies with both infants and adults (Phillips-Silver & Trainor, 2005, 2007, 2008). Participants either bounced themselves (adults) or had themselves bounced (infants) to an unaccented rhythm either in a duple

<sup>1</sup> Pitch chroma is that quality of a tone that distinguishes a C from a C#, independent of pitch height, and that gives rise to a common perception across all tones that we designate as C, regardless of octave.

(march) or triple (waltz) meter. The meter biased the perceptual representation and subsequent recall of the sequences. In effect, the movement itself created the (cross-modal) accented beat. This interactive process was found to be mediated by the vestibular system: although full body movement is the most effective in engendering the movement-sound interaction, head movement alone is capable of producing it, while body movement alone is not (Phillips-Silver & Trainor, 2008).

### Effects of Practice and Training

Early instrumental musical training appears to train attentional networks in the brain as well as to train social and interpersonal skills. Musically-trained children show improvements in nonverbal IQ, numeracy and spatial cognition (Neville et al., 2008). Children given music lessons showed improvements in verbal memory compared to a control group who received extended science training (Roden, Kreutz, & Bongard, 2012). Learning to play an instrument is associated with neurostructural changes (Besson & Schön, 2001; Wan & Schlaug, 2010) in children (Hyde et al., 2009) and adults (Bangert & Altenmüller, 2003). In particular, the brain regions responsible for movement of the fingers of the left hand is enlarged in violinists, compared to the analogous region for moving the right fingers, when compared to nonviolinists (Elbert, Pantev, Wienbruch, Rockstroh, & Taub, 1995). Gray matter (processing unit) differences are seen as well: gray matter volumes tend to be larger in musicians than nonmusicians for motor, auditory, and visuo-spatial brain regions (Gaser & Schlaug, 2003), and gray matter density is greater in Broca's area for trained musicians (Sluming et al., 2002). Moreover, nonmusicians showed reductions in gray matter volumes in dorsolateral prefrontal cortex and in gray matter density in left inferior frontal gyrus; musicians were spared such reductions (Sluming et al., 2002). The musicians' resistance to age-related neural decline parallel findings in the putamen for practitioners of Zen meditation, who also showed no declines relative to nonmeditators (Pagnoni & Cekic, 2007).

Learning to play an instrument as a child is associated with regional specific plasticity in myelinating tracts (Bengtsson et al., 2005). These changes were correlated with hours of practice and were especially pronounced in the corpus callosum—the dense bundle of fibers connecting the left and right hemispheres—and fiber tracts within the frontal lobes. The corpus callosum was also found to be larger in musicians versus nonmusicians (Schlaug, Jäncke, Huang, & Steinmetz, 1995).

Musicians show a number of advantages in nonmusical domains. Examples include an improved ability to hear speech embedded in noisy backgrounds (Parbery-Clark, Skoe, Lam, & Kraus, 2009), reduced age-related deficits in general auditory abilities (Parbery-Clark et al., 2011; Zendel & Alain, 2012), increased verbal and auditory memory (Chan, Ho, & Cheung, 1998; Ho, Cheung, & Chan, 2003), and enhanced auditory attention (Strait & Kraus, 2011; Strait, Kraus, Parbery-Clark, & Ashley, 2010).

Musicians show increased responses in the auditory cortex when listening to their instrument of expertise; for example,

violinists show increased responses to violin music, flutists to flute music, and so on (Margulis, Mlsna, Uppunda, Parrish, & Wong, 2009). Most North Americans are raised with exposure to a single musical system or culture (monomusical), and this parallels development in a home where one language is spoken (monolingual). Studies with bimusicals, individuals who are exposed to different musical systems or cultures (such as Indian and Western music), have shown that they use different parts of their brains to process music (Wong, Chan, Roy, & Margulis, 2011). Monomusicals differentiated Indian from Western music in auditory cortices, suggesting that the primary distinction they made was sensory or perceptual. Bimusicals differentiated these same musics in limbic structures, suggesting the distinction was more they made was primarily on an emotional or affective basis.

Effective connectivity analysis, a mathematical technique to measure the interaction of one brain region with another (Menon & Levitin, 2005), revealed a stronger connectivity in the bimusicals between such sensory-perceptual areas and the limbic system. This suggests that they were attending to deeper, emotional qualities of the music than were the monomusicals, who were arguably attending primarily to surface feature differences. The authors conclude that bimusicals enjoyed a more complex music-brain relationship, including greater integration between surface features and meaning, as instantiated in superior temporal gyrus (STG) and medial temporal gyrus (MTG) connectivity, as well as bidirectional amygdaloid activity.

Musical training has been shown to result in advantageous neural differences in speech processing. Electrical evoked potentials (electrical activity measured from various locations across the surface of the scalp, although difficult to localize) occur earlier and/or are larger in musically trained individuals (Bidelman, Gandour, & Krishnan, 2011; Musacchia, Sams, Skoe, & Kraus, 2007). Musical practice also enhances phase-locking in the brainstem to the fundamental frequencies of both musical and linguistic stimuli (Musacchia et al., 2007). When participants were presented with both audio and audiovisual stimuli in the domains of music and speech, musicians had an earlier onset and larger amplitude evoked brainstem response than nonmusicians. Because this response is a function of the amount of training as opposed to musical aptitude or basic pitch discrimination tasks, this finding gives empirical support for the saying "practice makes perfect." Additional studies also show regional changes in brain volume and in gray-to-white matter density as a function of musical practice (see Münte, Altenmüller, & Jäncke, 2002, for a review).

In general, increased training leads to a qualitative change in performance; operations that were effortful become automatic (Fitts & Posner, 1967). An example of automatic processing in music comes from a study of expert jazz musicians during the act of improvisation using fMRI (Limb & Braun, 2008). One might naturally assume that improvisation requires activation in the prefrontal cortex, that region of the brain most closely associated with planning and higher cognitive function in humans (Gazzaniga, 2008). In fact, strong patterns of *deactivation* were observed there, suggesting that conscious thought and volition needed to be

suppressed in order to improvise well. Activation was observed in neocortical sensory-motor areas that mediate organization and execution of musical performance. This pattern of activation and deactivation conforms to subjective reports by musicians that improvisation relies on sub- or preconscious processes that are outside the domain of conscious control and awareness. The lack of conscious control represents overlearned and automatic processes characteristic of experts in other fields of endeavor.

Thus, musical components are processed in distinctive and separable neural circuits. Musical activities engage a widely dispersed network of brain regions, not just so-called auditory regions. Musical training is typically associated with increases in gray matter volume and density, and helps to stave off age-related neural atrophy. Musical training is also typically associated with a left-ward shift in processing, reflecting the linguistic ability to label notes, intervals, and chords.

### Laterality Effects

For neurologically normal right-handed individuals music was originally thought to be represented in the right hemisphere, and language in the left (Bever & Chiarello, 1974). The present view is that music processing is bilateral, in part because of the distributed nature of specialized processing mechanisms for the individual musical attributes listed above. Listening, performing, and composing music activate regions bilaterally, in the cortex, neocortex, paleo- and neocerebellum (Peretz & Zatorre, 2003; Platel et al., 1997; Sergeant, 1993; Tramo, 2001). Laterality effects do exist, however. For example, MEG responses to deviations in the memorized lyrics of tunes are stronger in the left hemisphere, while the perception of violations of expected notes are governed by the right hemisphere (Yasui, Kaga, & Sakai, 2009). The act of learning music causes a leftward hemispheric shift (Ohnishi et al., 2001) particularly as naming processes become involved (such as naming musical intervals, chords, etc. (Peretz & Zatorre, 2005; Zatorre, 1998).

Simple tonal relations, or musical intervals (as opposed to strings of pitches, or melodies) have been shown to be predominantly served by networks in the right temporal region (Liégeois-Chauvel, Peretz, Babai, Laguitton, & Chauvel, 1998; Zatorre, 1985) and in the left dorsolateral prefrontal and right inferior frontal cortex (Zatorre, Perry, Beckett, Westbury, & Evans, 1998). Deficits in tonal relation processing followed lesions of the right anterolateral part of Heschl's gyrus (Johnsrude, Penhune, & Zatorre, 2000; Tramo, Shah, & Braid, 2002; Zatorre, 1998). When presented with a learning task for novel melodies in tonal and atonal contexts, patients with either left- or right-sided mesial temporal damage were impaired in interval recognition compared to normal controls. However, when memorizing melodies within a tonal context, individuals with right mesial temporal damage in particular were unable to use implicit knowledge of Western musical tonality to aid their memory (Wilson & Saling, 2008), suggesting hemispheric effects for stored tonal schemas.

### Language and Music

The relationship between language and music has been a topic of renewed interest in recent years (Patel, 2008). Both

rely on the hearing sense, and so there naturally exist overlapping circuits at the level of the ear, the cochlea, and the auditory nerve. For music with lyrics, the lyrics are generally processed in the same regions of the brain that process meaning in spoken or written language, semantic association networks, and the internal mental lexicon that include regions in the temporal lobes and hippocampus. The syntax of language is largely subserved by regions in the left frontal lobes, including Brodmann Areas 44, 45, and 47. While it is not clear whether a true syntax of music exists analogously to that of language, musical expectations and violations of those expectations are known to be processed in Brodmann Areas 44, 45, and 47 (Koelsch, 2005; Koelsch, Gunter, von Cramon, et al., 2002; Levitin & Menon, 2003). When presented with a chord sequence that resolves in an unexpected fashion, an electrical signal (the evoked response potential, or ERP) is observed similar to when participants hear or read a syntactic violation in a sentence (Koelsch, Jentschke, Sammler, & Mietschen, 2007). This response is called the ERAN (early right anterior negativity) and suggests strongly that the listening brain is building up schematic expectations for what a musical sequence will do, and reacts when that sequence is violated.

Patel (2003) proposed the Shared Syntactic Integration Resource Hypothesis (SSIRH), which stated that fronto-temporal neural resources for music and language overlap. This was confirmed experimentally (Levitin & Menon, 2003, 2005). A recent study using a more tightly controlled task and multivariate classification analysis revealed distinct spatial patterns of brain responses in the two domains. Distributed neuronal populations that included the inferior frontal cortex, the posterior and anterior superior and middle temporal gyri, and the auditory brainstem distinguished temporal structure manipulations in music from those in speech (Abrams et al., 2011). These temporal structure manipulations pitted music against scrambled versions of the same musical pieces (per Levitin & Menon, 2003). The scrambled versions retain the same overall loudness, pitch, and timbre distributions, while disrupting the listener's sense of expectation of what is coming next in the music. While these new findings agree with previous results that music and speech processing share neural substrates, this work reveals that the same neural resources operate in different modes, one for speech and one for music.

Attending to harmonic structure (Janata et al., 2002; Tillmann, Janata, & Bharucha, 2003) and the processing of harmonic anomalies (Koelsch, Gunter, von Cramon, et al., 2002; Maess, Koelsch, Gunter, & Friederici, 2001) have been shown to activate frontal lobe regions. An additional link between language and music comes from an experiment with children with specific language impairment (SLI; Jentschke, S., Sallat, & Friederici, 2008). Four- and five-year olds with SLI present a particular ERP pattern when listening to the final chord in a sequence, which violates harmonically lawful musical syntax. This response pattern deviates from that of children and adults who develop language typically, in that the SLI response elicited did not include an early right anterior negativity (ERAN) or the N5. Jentschke and colleagues (2008) further suggest that musical training may be a means of early intervention for children at risk for developing SLI.

Perceptual-cognitive processing of music can lead to emotional reactions, especially when lyrics are involved. Researchers distinguish between the experience of musical emotions and the mere recognition of them (Huron, 2011). That is, a listener can identify that a happy mood is intended in a piece of music without actually experiencing that happy mood. What are the processes involved when we do experience music-evoked emotions?

### Emotional Reactions to Music

Neural pathways carry the musical signal from the ear to the inferior colliculi in the midbrain, and then to emotional centers in the cerebellum, nucleus accumbens (NAc), ventral tegmental area (VTA), and amygdala; these regions are activated when people listen to pleasurable music, and dopamine levels are modulated as well (Menon & Levitin, 2005; Salimpoor, Benavoy, Larcher, Dagher, & Zatorre, 2011). The experience of pleasant or consonant music activates orbitofrontal, subcallosal cingulate, and frontal polar cortical areas (Blood, Zatorre, Bermudez, & Evans, 1999). Chills have been shown to correlate with activity in the left ventral striatum, an area mediating approach behavior to reward, the dorsomedial midbrain, and deactivation in the amygdala (Blood & Zatorre, 2001).

During music listening, the VTA mediates activity in the nucleus accumbens (NAc), hypothalamus, insula, and orbitofrontal cortex; this network represents the neural and neurochemical (via dopaminergic pathways) underpinnings of the anecdotal reports of pleasurable music (Menon & Levitin, 2005). In addition, the hippocampus has been found in PET studies to activate during pleasant music, and the parahippocampal gyrus, also implicated in emotion processing, has been found to activate during dissonant music (Koelsch, 2006). This network of structures, which includes the amygdala and the temporal poles, is thought to be the neurological basis for the emotional processing of music (Koelsch, 2006).

The neurochemical mechanism by which music induces pleasure probably involves the dopaminergic system mentioned above, as well as serotonin and the brain's own endogenous opioids (Chanda & Levitin, 2013). One piece of evidence for the latter is that the administration of naloxone, a known opioid antagonist, blocks musical pleasure (Goldstein, 1980).

The neuroanatomical substrates of emotion regulation in music were studied in a group of postoperative epileptics (Khalifa et al., 2008) with temporal lobe resections (including the amygdala). Patients with right hemisphere resection showed a reduced ability to recognize sad music (and they overidentified happy music) whereas patients with left hemisphere resections showed reduced recognition of both happy and sad music. These findings must be interpreted with caution because the experiment did not evaluate the preservation of lower level perceptual function in the patients following surgery; that is, the presence of basic pitch or contour deficits could underlie the participants' judgment of emotion in the music. Nonetheless, this suggests a role of the temporal lobe and amygdala in recognizing emotions in music.

Many listeners report using music for mood regulation, and may find comfort in sad music (Chamorro-Premuzic & Furnham, 2007). One might think that sad people would find happy music an antidote to their mood, but this is not always the case. Prolactin, a tranquilizing and consoling hormone, is produced by the anterior pituitary gland when we are sad (Huron, 2006; Panksepp, 2006). The evolutionary purpose of sorrow, Huron (2006) explains, is to aid in energy conservation and allow for reassessment of priorities for the future following a traumatic event. Prolactin is released after orgasm, after birth, and during lactation in females.

A chemical analysis reveals that prolactin is not always present in tears—it is not released in tears of lubrication of the eye, or when the eye is irritated, or in tears of joy; it is only released in tears of sorrow. Huron speculates that sad music allows us to “trick” our brains into releasing prolactin in response to the safe or imaginary sorrow induced by the music, and the prolactin then reverses our moods. Aside from the neurochemical story, there is a more psychological or behavioral explanation for why we find sad music consoling. When people feel sad or suffer from clinical depression, they often sense being cut off from other people, feeling as though no one understands them. Happy music can be especially irritating because it makes them feel even less understood. Sad music may be consoling because it connects the listener to others who seem to be experiencing a similar affective state (Friedman, Gordis, & Förster, 2012; Huron, 2011; Knobloch, Weisbach, & Zillmann, 2004; Zillmann, 2000).

The aforementioned studies refer to the emotional reactions of individuals *listening* to music. Playing music together is believed to promote a sense of empathy and social bonding (Chanda & Levitin, 2013); the mechanism of this is putatively through the synchronization of motor, action planning, and sensory neural networks, and closer coupling of such activations (through better performance synchrony) results in increased communication among individuals (Overy, 2012). Contrary to this, some musicians report anecdotally that they don't find enjoyment from performing and composing, and yet they feel a strong drive to engage in these activities. The topic warrants further investigation.

### Effects of Music on Immune Function and Health

The notion that “music is medicine” has roots that extend deep into our past through healing rituals practiced in preindustrial, tribal-based societies. In ancient Greece music was prescribed to patients to restore and maintain health (Merriam, 1964; White, 2001). Following the invention of sound recording (White, 2001), the early 1900s saw a rise in the use of recorded music by health care practitioners in conjunction with anesthesia and analgesia (Taylor, 1981), and to distract patients from the horrors of surgery (Kane, 1914). Music activates diverse brain networks, including those for cognition, emotion, motor control, and attention (Koelsch, 2011; Levitin & Tirovolas, 2009; Tramo, 2001); it can create powerful, long-term effects on individuals, even in domains outside of music (Kraus & Chandrasekaran, 2010; Moreno et al., 2011; Patel, 2010; Wong, Skoe, Russo, Dees, & Kraus, 2007).

In contemporary society, music continues to be used to promote health and well-being in clinical settings, such as for pain management, relaxation, psychotherapy, and personal growth (see Chanda & Levitin, 2013, and Kreutz, Quiroga Murcia & Bongard, 2012 for reviews). Although music therapy interventions are based strongly on clinical-practice knowledge, concepts from evidence-based practice and experiments are providing additional information about the specificity of these interventions. Indeed, the American Music Therapy Association (2011) defines its practices as relying on the "evidence-based use of music."

For athletes, stamina, motivation (Becker et al., 1994; Simpson & Karageorghis, 2006), and anaerobic power (Eliakim, Meckel, Nemet, & Eliakim, 2007) can be improved by listening to music during sports activities and workouts. Indeed, the Ethiopian runner Haile Gebreselassie (who won the Olympic gold medal at 10,000 meters) broke the indoor 2000-meter world record in February 1998 while listening to music, by synchronizing his stride to the techno song *Scatman* by Scatman John (Karageorghis, 1998; Kurutz, 2008).

One intriguing line of work on the benefits of music to health suggests that music making helps to regulate breathing and heart rate (Osborne, 2012). Posttraumatic stress disorder (PTSD) and stress, which are known to affect these autonomic systems, can perhaps be alleviated through breathing, singing, and playing wind instruments. Another marker of PTSD is dysregulation of motor movements which can also be improved through playing music (Osborne, 2012), and shared music making confers psychosocial benefits that can aid victims of trauma (Osborne, 2012).

There exists a small body of evidence that music modulates the physiological stress responses (Chanda & Levitin, 2013; Kreutz, Quiroga Murcia, & Bongard, 2012). Relaxing music produces decreases and stimulating music produces increases in markers of stress and arousal, specifically heart rate, blood pressure, respiratory rate, skin conductance, and in HPA (hypothalamic-pituitary adrenal) axis activity, such as cortisol levels.

Listening to "relaxing music" (generally considered to have slow tempo, low pitch, and without lyrics) has been shown to reduce stress and anxiety in healthy subjects (Dileo & Bradt, 2007; Knight & Rickard, 2001), patients undergoing invasive medical procedures (e.g., surgery, colonoscopy, dental procedures) (Cepeda, Carr, Lau, & Alvarez, 2006; Nilsson, 2008; Pittman & Kridli, 2011; Tam, Wong, & Twinn, 2008), pediatric patients undergoing medical procedures (Klassen, Liang, Tjosvold, Klassen, & Hartling, 2008), and patients with coronary heart disease (Bradt & Dileo, 2009). Music listening following painful medical procedures (e.g., surgery) has also been found to reduce sedation requirements, pain, and analgesic requirements (Cepeda et al., 2006; Mitchell & MacDonald, 2006; Nilsson, 2008), although the effect sizes are small.

The effects of relaxing music on stress hormone levels, including cortisol, have also been investigated in healthy subjects at rest (Grape, Sandgren, Hansson, Ericson, & Theorell, 2003; Kreutz, Bongard, Rohrmann, Hodapp, & Grebe, 2004), in combination with imagery (McKinney, Antoni, Kumar, Tims, & McCabe, 1997; McKinney, Tims,

Kumar, & Kumar, 1997) and during stressful tasks (Khalfa, Dalla Bella, Roy, Peretz, & Lupien, 2003; Knight & Rickard, 2001). These results suggest that music can function effectively to reduce stress across a variety of situations in the home, workplace, and in clinical settings.

The mechanism for stress reduction likely involves a reduction in central nervous system arousal levels. Because some neuronal populations fire in synchrony with the tempo of music, slow tempo music could lead to reductions in heart and respiration rates. Music initiates reflexive brain stem responses, mediating heart rate, pulse, blood pressure, body temperature, skin conductance, and muscle tension (Juslin & Västjäll, 2008; Lundqvist et al., 2009).

Music listening and performance appear to improve immune system function (Chanda & Levitin, 2013; Gangrade, 2012; Lane, 1994; Wachi et al., 2007). Specifically, increases have been shown in salivary immunoglobulin A (s-IgA), a principal immunoglobulin secreted externally in body fluids including saliva and mucus of the bronchial, genitourinary, and digestive tracts (Woof & Kerr, 2006). s-IgA is a first line of defense against bacterial and viral infections (Woof & Kerr, 2006), and a reliable marker of the functional status of the entire mucosal immune system (Mestecky, 1993). Three independent studies reported increases in s-IgA concentration following group singing (Beck, Cesario, Yousefi, & Enamoto, 2000; Kreutz et al., 2004; Kuhn, 2002).

Music may also be an effective primary or adjunct therapy in dealing with mental disorders of various kinds (de l'Etoile, 2002, 2005; Gold, Voracek, & Wigram, 2004; Unkefer, 2005). In one study, aggression was reduced in preadolescents with behavior disorders, regardless of whether the music therapy involved music making or music listening (Montello & Coons, 1999). However, the power of the group activity and possible oxytocin release cannot be ruled out as proximal causes, rather than the musical activities themselves. In another study, music therapy was found to decrease symptoms of dementia and increase the quality of the relationship between the patient and the therapist compared to control activities (Raglio et al., 2008).

Music may reduce stress and protect against disease, either as a routine part of daily life, or in the context of therapist-directed interventions. The therapist-patient interaction is likely to be an important factor in the efficacy of such interventions. Another dimension crucial to consider for the clinician is locus of control (Knappe & Pinquart, 2009; Leftcourt, 1976)—patients are more likely to experience beneficial effects of musical interventions if they perceive that they were involved in the decision about what particular music to play.

### Summary

Musical activities activate a widespread network of brain regions, in both cerebral hemispheres, and subcortically as well, including the brain stem, pons, and cerebellum. Musical experience leads to structural changes in the brain, including increased gray matter density and volumes, and can slow age-related declines. Musical emotions are subserved by a network invoking the well-known pleasure center of the brain, including the nucleus accumbens, ventral tegmental

area, and the modulation of the neurochemical dopamine. Music has been shown to improve immune system function through the modulation of IgA. Music has also been found to modulate the stress response, and reduce the need for analgesics and pain relievers.

The use of music for health outcomes is found in many preindustrial societies and was well known to the ancient Greeks. The past three decades have seen modern experimental methods brought to bear on the question of whether the effects are genuine, and whether they are attributable to music per se as opposed to ancillary or confounding factors. A great deal has been discovered about the neuroanatomical basis for music (Levitin & Tirovolas, 2009) whereas less is known about its neurochemical basis.

The emerging picture is that music can play an important role in bolstering the physical and psychological health of already healthy individuals, and in the treatment of patients across a wide range of presentations. The advantage of music-based treatments is that they are noninvasive, don't have side-effects, are cost-effective, and completely "natural." Consider, for example, the standard for presurgical anxiety reduction, benzodiazepines. They are effective, but have a high incidence of unwanted side effects including amnesia, and paradoxical agitation and hyperactivity. The amnesia, in addition to being stressful, can cause patients to forget physician instructions (Chanda & Levitin, 2013).

There is a great need in the field for research that involves (a) controlled experiments with random assignment, (b) well-matched stimuli and control conditions in order to uncover the mechanisms by which music works, (c) a better understanding of the neurochemical systems involved, and (d) the optimal role of the music therapist in such interventions.

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