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Music Making as a Tool for Promoting Brain Plasticity across the Life Span

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Abstract

Playing a musical instrument is an intense, multisensory, and motor experience that usually commences at an early age and requires the acquisition and maintenance of a range of skills over the course of a musician's lifetime. Thus, musicians offer an excellent human model for studying the brain effects of acquiring specialized sensorimotor skills. For example, musicians learn and repeatedly practice the association of motor actions with specific sound and visual patterns (musical notation) while receiving continuous multisensory feedback. This association learning can strengthen connections between auditory and motor regions (e.g., arcuate fasciculus) while activating multimodal integration regions (e.g., around the intraparietal sulcus). We argue that training of this neural network may produce cross-modal effects on other behavioral or cognitive operations that draw on this network. Plasticity in this network may explain some of the sensorimotor and cognitive enhancements that have been associated with music training. These enhancements suggest the potential for music making as an interactive treatment or intervention for neurological and developmental disorders, as well as those associated with normal aging.

Keywords

auditory; diffusion tensor imaging; functional MRI; morphometry; motor; music; plasticity

Plasticity is a fundamental organizational feature of human brain function. Traditionally, the brain was thought to be hardwired following a critical period in development. However, it is now accepted that the brain has a remarkable capacity to modify its structural and functional organization throughout the life span, in response to changes in environmental input. This brain plasticity underlies normal development and maturation, skill learning and memory, recovery from injury, as well as the consequences of sensory deprivation or environmental enrichment.

Skill learning offers a useful model for studying plasticity because it can be easily manipulated in an experimental setting. In particular, music making (e.g., learning to sing or to play a musical instrument) is an activity that is typically started early in life, while the brain is most sensitive to plastic changes, and is often continued throughout life by musicians. Furthermore, music making involves multiple sensory modalities and motor planning, preparation, and execution systems (Schlaug and others 2010). The idea that

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musical training can be a strong multimodal stimulator for brain plasticity can be traced back to the early 20th century, when Ramon y Cajal (1904/1999) argued that music expertise is associated with anatomical changes in the brain:

> Everybody knows that the ability of a pianist [. . . to play an] adaptation to the new work [. . .] requires many years of mental and muscular gymnastics. To understand this important phenomenon, it is necessary to accept that, in addition to the reinforcement of pre-established organic pathways, new pathways are created by the ramification and progressive growth of terminal dendritic and axonal processes. (p 541)

Music making places unique demands on the nervous system and leads to a strong coupling of perception and action mediated by sensory, motor, and multimodal integrative regions distributed throughout the brain (Schlaug and others 2010). Playing an instrument, for example, requires a host of skills, including reading a complex symbolic system (musical notation) and translating it into sequential, bimanual motor activity dependent on multi-sensory feedback; developing fine motor skills coupled with metric precision; memorizing long musical passages; and improvising within given musical parameters. Indeed, research over the past 2 decades has demonstrated that intense musical training can result in plastic changes in the developing brain as well as the adult brain (Gaser and Schlaug 2003; Hyde and others 2009).

This review summarizes research on the effects of musical training on the structural and functional organization of the human brain. Engaging in musical activities not only shapes the organization of the developing brain but also produces long-lasting changes even after brain maturation is complete. The fact that the adult brain can undergo continual modifications highlights the potential of rehabilitation treatments that are designed to induce plastic changes to overcome impairments due to brain injury. For this purpose, music may be a suitable medium because it transmits visual, auditory, and motor information to a specialized brain network consisting of frontotemporoparietal regions. These brain regions overlap with a “hearing-doing” or “seeing-doing” action-observation network that is commonly known as the mirror neuron system (Wan and others 2010b; Lahav and others 2007). In addition, listening to music or playing music is known to provoke emotions as well as increase interpersonal communications and interactions. Because music making can be experienced as a pleasurable activity through its involvement in the limbic system, individuals are likely to sustain motivation to engage in an intensive training program that involves music.

The remainder of this review is divided into 3 main sections: 1) the effects of instrumental music training on brain development in children; 2) the capacity of musical activities to induce reorganization in the adult brain; and 3) the potential utility of music making to suspend or to counter effects associated with the normal aging process.

Brain and Behavioral Effects of Musical Training in Children

Cross-Sectional (or Correlational) Studies

Longitudinal studies are ideal for investigating skill transfer because performance improvement as a function of music practice can be easily documented within the same individual. Most research studies to date, however, are cross-sectional. In these cross-sectional studies, it is often difficult to draw strong inferences about the effects of musical training on cognitive performance. This is because factors such as higher socioeconomic status, greater availability of resources at school, superior motivational skills, more supportive home environment, or higher prior IQ could account for some of the cognitive advantages obs erved in the musically trained children. Nevertheless, cross-sectional studies represent a good starting point for elucidating the potential benefits of musical training, to define the areas that might be enhanced, and to determine the power necessary to detect changes in longitudinal studies examining causal effects. Nevertheless, ultimately, longitudinal studies are crucial in determining the relative contribution of “nature” and “nurture” in skill development and whether group differences in cross-sectional studies are due to long-term skill training or other preexisting factors that could favor one group to develop particular skills (Fig. 1).

Learning to play a musical instrument in childhood can result in long-lasting changes in brain organization. The first study that examined neuroanatomical differences between musicians and nonmusicians reported larger anterior corpus callosum in musicians (Schlaug and others 1995a), a finding that has since been replicated by different research groups using different methodological approaches (Oztürk and others 2002; Lee and others 2003; Hyde and others 2009). The corpus callosum plays an important role in interhemispheric communication, which underlies the execution of complex bimanual motor sequences. Moreover, musicians who began training at an early age (≤7 years) had a significantly larger corpus callosum compared to musicians who started later (Fig. 2 A and B). A similar finding was also observed in motor regions. In particular, the depth of the central sulcus, often used as a marker of primary motor cortex size, was larger on both hemispheres but most pronounced on the right hemisphere for musicians compared to nonmusicians, possibly due to years of manual motor practice emphasizing the nondominant hand (Amunts and others 1997; Schlaug 2001). As was observed for the corpus callosum, there was a positive correlation between the size of the primary motor cortex and the onset of instrumental musical training (used as a surrogate for intensity and duration of training).

Structural brain differences between different musician groups (e.g., keyboard and string players) are consistent with a “nurture” hypothesis (Bangert and Schlaug 2006). The omega sign, an anatomical landmark of the precentral gyrus associated with hand and finger movement representation, was found to be more prominent on the left hemisphere for keyboard players but was more prominent on the right hemisphere for string players (Fig. 3). This structural difference between different musician groups is very pronounced and most likely represents an adaptation to the specific demands of different musical instruments. Alternatively, it is possible that certain preexisting anatomical features might favor the study of certain instruments, although this would still be consistent with the findings that brain regions adapt on a microstructural level. The sum of these microstructural changes may amount to differences that could be detected on a macro-structural level with current neuroimaging techniques.

Additional studies have also reported structural differences between musicians and nonmusicians in regions such as the planum temporale, or secondary auditory cortex (Keenan and others 2001; Loui and others 2010; Schlaug and others 1995b; Schulze and others 2009; Zatorre and others 1998). A pronounced leftward asymmetry of the planum temporale was linked to the ability to perceive absolute pitch. Other areas showing differences included the Heschl gyrus, or primary auditory cortex (Schneider and others 2005), the Broca area, and the inferior frontal gyrus in general (Sluming and others 2002; Gaser and Schlaug 2003). These structural differences appear to be more pronounced in those musicians who began training early in life (Elbert and others 1995; Schlaug and others 1995a) and who practiced with greater intensity (Gaser and Schlaug 2003; Hutchinson and others 2003; Schneider and others 2005).

Intensive musical training can also be associated with an expansion of functional representation of finger or hand maps. In string players, for example, the somatosensory representations of their playing fingers were found to be larger compared to those of nonmusicians (Pantev and others 2001). This effect was more pronounced for the fifth digit, which was rarely used in the nonmusician group. Musicians who had begun training early in life demonstrated larger cortical representation of their left fifth digit compared to those who started to play their instruments later (after 13 years), who in turn had larger representations than the nonmusicians. In addition to these enhanced somatosensory representations, musicians also have larger representations for tones than do nonmusicians. In one study, musicians who had started playing at a young age demonstrated the largest cortical representations (Pantev and others 1998), although this enlargement was evident for only piano tones but not pure tones. In contrast, a study by Schneider and others (2002) reported increased representation for pure tones, up to twice as large in professional musicians compared to nonmusicians. In that study, amateur musicians showed an intermediate increase over nonmusicians but only for tones less than 1000 Hz. In sum, increased training and exposure to musical stimuli may lead to enlargement of representation in the somatosensory and auditory regions.

Recent advances in neuroimaging have led to the use of diffusion tensor imaging (DTI) to examine white matter anatomy of the human brain. A handful of studies have investigated differences in white matter architecture between musicians and nonmusicians, although with inconsistent results. DTI-derived measures such as fractional anisotropy (FA) can measure the directionality of water diffusion and is a measure of the coherence of aligned fibers. The higher the FA value, the more aligned fibers are in a specific direction (Beaulieu 2002). Axial diffusivity is a measure of water diffusion along the main direction of a tract and a measure of axonal integrity (Song and others 2002). Radial diffusivity is a measure of water diffusion perpendicular to the main direction of a tract or an indicator of myelination (Budde and others 2007). Schmithorst and Wilke (2002) found that musicians had lower FA in the internal capsules but higher FA in the corpus callosum. In contrast, Bengtsson and others (2005) reported higher FA in the internal capsule. They also found that the number of practice hours during childhood was positively correlated with increased FA values not only in the internal capsule but also in the corpus callosum and the superior longitudinal fasciculus. More recently, Imfeld and others (2009) found lower FA in the corticospinal tracts of musicians compared to nonmusicians. Musicians who began training before 7 years of age were found to have increased mean diffusivity in the corticospinal tract compared to musicians who began training later and to nonmusicians. Consistent with previous results, the training-induced plasticity in musicians appears to be most prominent in those who engaged in practice early in childhood. We show the differential development of the arcuate fasciculus comparing 2 DTI studies separated by 2 years in a child with and one without instrumental music training (Fig. 4). The arcuate fasciculus is an auditory-motor fiber tract that is of critical importance in mapping sounds with actions. Figure 4 shows an exaggerated development of the 2 components of this fiber tract particularly on the right hemisphere in the child who has studied a string instrument for the 2 years in between the 2 imaging studies.

Developing and strengthening connections between brain regions and plastic changes in multisensory integration regions may also have an effect outside of the music domain. A growing body of evidence has pointed to the beneficial effects of musical training on the cognitive development in children. These studies help us to understand how the developing brain can be sculpted by musical experience and whether musical training leads to enhanced abilities in other domains, or skill transfer (Bangerter and Heath 2004). Skill transfer can be classified into 2 broad categories: 1) near transfer, when there is a close resemblance between training and transfer domains; and 2) far transfer, when the relationship between the resemblance between training and transfer domains is less obvious. Near-transfer effects of musical training on auditory perception and fine motor abilities have been consistently observed. Cross-sectional studies have reported that musically trained children are better at pitch and rhythmic discrimination (Forgeard and others 2008) and melodic contour perception (Morrongiello and Roes 1990) and have faster finger-sequencing abilities (Forgeard and others 2008) compared to untrained children. Far-transfer effects of musical training, although mostly based on cross-sectional studies, have also been reported in the areas of spatial, verbal, and mathematical performances, as well as in general IQ. Some researchers believe that music training could enhance spatial reasoning skills because the ability to read music notation requires the representation of pitches on a series of lines and spaces (Hetland 2000; Rauscher and Zupan 2000). However, out of 13 studies examining the relationship between music training and spatial abilities, 5 reported positive associations, while the remaining 8 had negative, null, or mixed results (Hetland 2000). The evidence for transfer effects from music training to spatial skills therefore remains inconclusive.

Parallels between music and language suggest that musical training may lead to enhanced verbal abilities. Children with language disorders, in particular, may benefit from intensive musical training because of the overlapping responses to music and language stimuli in the brain. For instance, fMRI studies have reported activation of the Broca area during music perception tasks (e.g., Koelsch and others 2002; Tillmann and others 2003), active music tasks such as singing (e.g., Ozdemir and others 2006), and even when participants imagined playing an instrument (e.g., Meister and others 2004; Baumann and others 2007). Moreover, a common network appears to support the sensorimotor components for both speaking and singing (e.g., Pulvermuller 2005; Ozdemir and others 2006; Kleber and others 2010). Indeed, a number of studies have reported an association between music and language skills. For example, pitch perception was positively correlated with phonemic awareness and reading abilities in children (Anvari and others 2002). Similarly, years of musical training predicted verbal recall (Jakobson and others 2003). A meta-analysis of 25 cross-sectional studies found a significant association between music training and reading skills (Butzlaff 2000).

Another domain that has been implicated in the far-transfer effects of musical training is mathematical performance. A meta-analysis of 6 studies examining this relationship found that only 2 studies reported a positive effect (Vaughn 2000). Furthermore, a recent cross-sectional study did not find superior mathematical abilities in musically trained children (Forgeard and others 2008). Thus, there appears to be little evidence demonstrating a transfer of skills between music and mathematics.

Higher IQ has also been reported in children who have received musical training. For example, engaging in musical practice in childhood predicted academic performance and IQ at the university level (Schellenberg 2006). This effect persisted even when family income and parents' education were controlled for. Thus, there appears to be some support for the effects of music lessons on intellectual development.

In a cross-sectional study that examined both near-and far-transfer effects, Schlaug and others (2005) compared a group of 9- to 11-year-old instrumentalists (who had an average of 4 years of training) with a group of noninstrumentalists matched on age, handedness, and socioeconomic status. They observed differences in both cognitive abilities and brain organization. Specifically, the instrumental group performed significantly better on auditory, motor, and vocabulary tasks, and similar trends were also evident in abstract reasoning and mathematical skills. Regarding brain differences, the instrumentalists had larger gray matter volumes in the sensorimotor cortex and the occipital lobe. Using fMRI, instrumentalists also showed greater activation in the superior temporal gyrus, posterior inferior frontal gyrus, and middle frontal gyrus during tasks involving melodic and rhythmic discrimination. The stronger involvement of the inferior and middle frontal regions in the instrumental group suggests an enhanced ability to integrate auditory signals with other sensorimotor information. Moreover, these regions overlap with the mirror neuron system, which contains neurons that respond both when an action is observed and when that same action is performed (Lahav and others 2007). For example, the music student learns by watching the teacher and/or conductor, by listening to the sounds that are produced by particular types of movement, by evaluating self-produced sounds, sometimes in combination with sounds produced by other musicians, and by translating visual symbols into sound. As illustrated in Figure 5, the involvement of brain regions that are believed to contain mirror neurons (e.g., posterior inferior frontal gyrus) during music perception is enhanced in musicians compared with nonmusicians.

Longitudinal Studies

One of the criticisms of cross-sectional studies is that preexisting differences in brain organization and cognitive skills (rather than musical training) could account for some of the discrepancies between musicians and non-musicians. To investigate this possibility, 5- to 7-year-old children were assessed prior to starting instrumental music lessons, and their results were compared with those of controls matched on age, socioeconomic status, and verbal IQ (Schlaug and others 2005). No significant pre-existing cognitive, music, motor, or structural brain differences between the instrumental and control groups were found (Norton and others 2005). Thus, it is unlikely that children who choose to play a musical instrument do so because they have an unusual set of cognitive skills or patterns of brain organization. The differences observed between musically trained individuals and controls are likely to be due to intensive learning rather than to preexisting biological markers of musicality.

Longitudinal studies have provided converging evidence for both near- and far-transfer effects. Relative to matched controls, children who received music lessons showed greater improvement in pitch and rhythmic auditory discrimination (Flohr 1981), the ability to tap synchronously with a metronome (Hurwitz and others 1975), and fine motor sequencing (Forgeard and others 2008). In terms of far-transfer effects, musically trained children exhibit superior verbal memory abilities (Ho and others 2003). After 1 year of instrumental music training, children who continued music training showed greater improvement in verbal memory, whereas those who had discontinued training did not improve. In another study, children who participated in a 36-week music program (which involved either small group singing or playing the keyboard in a group with relatively little weekly practice time) had an increase in IQ compared to children who had received no additional lessons or only drama lessons (Schellenberg 2004). In that study, children who practiced singing showed greater increase in IQ compared to those who played the keyboard, suggesting that vocal music making might have different effects than instrumental music making. In another study, a training program that incorporated visual-auditory associations (including the use of musical notation) improved the writing skills of children with developmental dyslexia (Kast and others 2007). Recently, Moreno and others (2009) reported that children who received music lessons for 6 months showed improvements in reading and linguistic perception abilities, but no such improvement was observed in children who received painting lessons. The behavioral enhancements in the musically trained children were also accompanied by changes in the amplitudes of specific event-related potentials (ERP) components associated with music and speech.

More compelling evidence comes from longitudinal studies that measured changes in brain anatomy across separate time points as a function of musical practice. Hyde and others (2009) found that 6-year-old children showed structural brain changes after receiving musical training for 15 months in regions such as the precentral gyrus, the corpus callosum (Fig. 2D), and the Heschl gyrus. These brain changes correlated with performance on various auditory and motor tasks. Overall, these findings indicate that plasticity can occur in brain regions that control sensory functions important for playing a musical instrument. The malleability of the developing brain implies that interventions that target multisensory regions can facilitate plasticity in children and be used to treat certain developmental disorders.

Brain Plasticity Is Possible in Adulthood

Recent research has demonstrated that training-induced plasticity is not restricted to the developing brain. Even in the mature brain, increased reliance of a particular skill or a body part can lead to structural modifications. For example, Maguire and others (2000) found that taxi drivers had larger posterior hippocampi than did controls (non–taxi drivers), and the amount of time spent as a taxi driver predicted larger hippocampal volumes. Although these between-group structural *differences* do not necessarily imply structural *changes*, they nonetheless provide information about potential causality. Structural changes in brain anatomy have been observed in longitudinal studies that examined the effects of intensive skill learning on the adult brain. Individuals (20 years old) who had learned to juggle daily for 3 months showed increased gray matter volume in the midtemporal area (Draganski and others 2004), but these changes returned to baseline levels 3 months after cessation of juggling. Similar outcomes were also observed when elderly individuals (60 years old) learned to juggle under the same experimental conditions (Boyke and others 2008). Interestingly, a different study, which focused on DTI-derived measures, found that learning to juggle led to changes in parietal regions (Scholz and others 2009). In another study, students who engaged in daily study sessions for 3 months in preparation for a medical examination showed increases in gray matter volume in the posterior parietal regions and the hippocampus (Draganski and others 2006). Together, these studies demonstrate the malleability of the mature brain; that is, intensive skills learning in adulthood can induce structural adaptations that allow the brain to accommodate the demands of the environment.

Although no research in the music domain has directly investigated structural plasticity in the healthy adult brain, recent studies have reported functional changes in the brain following relatively short-term musical training in adulthood. For example, adult nonmusicians who learned to play a musical sequence on the piano over a 2-week period showed larger mismatch negativity in the auditory cortex compared to baseline (Lappe and others 2008). In another longitudinal study, the neural responses of music academy students in acoustic novelty detection were compared before and after 2 semesters of intensive aural skills training (Herdener and others 2010). Increased responses in the hippocampus following the training period were observed using fMRI. This was also the first study to show that functional plasticity is possible in the adult hippocampus.

Training Can Slow Cognitive Decline in the Elderly

Aging is associated with the progressive loss of function across various domains including perception, cognition, memory, and motor control. Although brain plasticity is known to occur throughout the life span, the degree of plasticity typically declines with age (Berardi and others 2000; Stiles 2000). This relationship has been shown in studies of recovery from brain injuries (e.g., Mahncke and others 2006; Mosch and others 2005). Brain injury during childhood results in less severe behavioral and cognitive deficits than comparable injury in adulthood, although recovery from injury may still be possible in the adult brain (Kolb 1995).

The developmental limits in brain plasticity have been characterized in neurophysiological studies. Studies of nonhuman primates have shown that 35% of axons and neurons disappear between the peak of development and adulthood. In humans, the adult synaptic density is only 60% of the maximum density that is reached during development (Huttenlocher and Decourten 1987). Studies have shown that perceptual motor performance, such as reaction time, speed of movement, and motor coordination, declines with age (e.g., Kauranen and Vanharanta 1996; Guan and Wade 2000). In addition to behavioral decline, a number of studies have reported reductions in frontal brain volumes with age (e.g., Jäncke 2004; Sowell and others 2004; Apostolova and Thompson 2008). Degeneration of brain tissues and cognitive decline may represent an inevitable trajectory of the normal aging process.

The effects of intensive training on the aging adult brain have been investigated by a handful of studies. For example, Sluming and others (2002) reported that practicing musicians have greater gray matter volume in the left inferior frontal gyrus compared to that of matched nonmusicians. For the nonmusicians, significant age-related reductions in total brain volumes and in regions such as the dorsolateral prefrontal cortex and the left inferior frontal gyrus were not observed in musicians. Thus, musicians appear to be less susceptible to age-related degenerations in the brain, presumably as a result of their daily musical activities (Fig. 6). In their juggling study, Boyke and others (2008) observed that 60-year-old elderly individuals were able to learn 3-ball cascade juggling but with less proficiency compared with young adults. Nonetheless, these elderly individuals showed gray matter increases in the midtemporal area, the hippocampus, and the nucleus accumbens. Taken together, these findings suggest the potential value of plasticity-based training in preserving brain functions in the elderly.

The human aging process is often associated with reduced schedules of activities, resulting in overall brain disuse (Mahncke and others 2006). As people age, they tend to engage less in cognitive-demanding activities, particularly in the case of retirement. This reduced activity may further undermine the learning and memory capacities of the elderly. The idea that age-related cognitive decline may be slowed, arrested, or even reversed through appropriately designed training or activities is supported by some research. Studies have shown that the frequency of cognitive activities in the elderly is associated with lower risk of cognitive disorders such as dementia. For example, elderly participants who were diagnosed with dementia were assessed on the overall frequency of cognitive activities: reading, writing, crossword puzzles, games, group discussions, or playing music (Hall and others 2009). Increasing frequency of cognitive activities predicted a delay in the onset of accelerated memory decline. In a longitudinal study, the relative contribution of specific activities was investigated (Verghese and others 2003). Participants aged over 75 years were followed for 5 years. Those participants who frequently played a musical instrument were less likely to have developed dementia compared to those who rarely played a musical instrument. This protective effect of playing music was stronger than those of other cognitive activities such as reading, writing, or doing crossword puzzles. Physical activities (e.g., walking, swimming) did not appear to confer any protective benefit in the development of dementia.

To minimize the deleterious effects of aging on brain function, elderly individuals need to engage in demanding multisensory, cognitive, and motor activities on an intensive basis. Accordingly, a training program that is designed specifically to facilitate brain plasticity, or engage multiple brain regions (especially the frontal and prefrontal areas), may counteract some of the negative consequences underlying disuse associated with aging. One activity that has the potential to stimulate and preserve cognition is music making. The beneficial effects of playing music in old age were examined in an experimental study in which musically naïve elderly participants (aged 60–85 years) were randomly allocated to an experimental group (6 months of intensive piano lessons) or a no-treatment control group (Bugos and others 2007). The experimental group received a half-hour lesson each week and was required to practice independently for a minimum of 3 hours per week. Following this period of musical training, they showed improvements on tests of working memory, perceptual speed, and motor skills, while the control group did not show such improvements.

Concluding Remarks

Over the past decade, there has been increasing evidence describing the cognitive and brain effects of music making in both children and adults. Music making involves a combination of sensory, cognitive, and motor functions. Engaging in musical activities may result in improved performances in related cognitive domains, although its effects on more distant domains remain unclear. One possible interpretation is that of cross-modal transfer plasticity: that is, music making leads to changes in poly-modal integration regions (e.g., regions surrounding the intraparietal sulcus), which may alter task performance in other domains. For example, instrumental music making has been shown to lead to structural and functional changes in the vicinity of the intraparietal sulcus (Fig. 7A). The intraparietal sulcus (IPS) region has also been found to be the region for neural representation of all types of numerical representation and operations (Dehaene 1997;Dehaene and others 1998;Pinel and others 2004;Piazza and others 2007;Cohen Kadosh and others 2007) (Fig. 7B). Thus, adaptations in brain regions that are involved in musical tasks may have an effect on mathematical performance because of shared neural resources in the vicinity of the IPS, which could be involved in the meaning of symbols and the mental manipulation of symbolic representation. The studies reviewed here have provided compelling evidence for brain plasticity following musical training, with adaptations observed not only in the primary and secondary motor and auditory regions of the brain but also in multi-modal integration regions in the frontal and parietal regions. Music training in children, when commenced at a young age, results in improved cognitive performance and possibly the development of exceptional musical abilities such as absolute pitch. Because the human brain can be shaped by musical experience, one promising application of a music-making program is in the treatment of neurological and developmental disorders (Schlaug and others 2010;Wan and others 2010a). Research to date has indicated functional improvements following an intensive music-based training program. However, longitudinal stu dies that examine the efficacy of music making in clinical settings are still limited but beginning to emerge (Schlaug and others 2009;Wan and others 2010a;Schlaug 2009;Schneider and others 2010). It is our hope that the use of music making as a therapeutic strategy will continue to be tested in future studies and ultimately be applied to the treatment of various neurological and developmental conditions.

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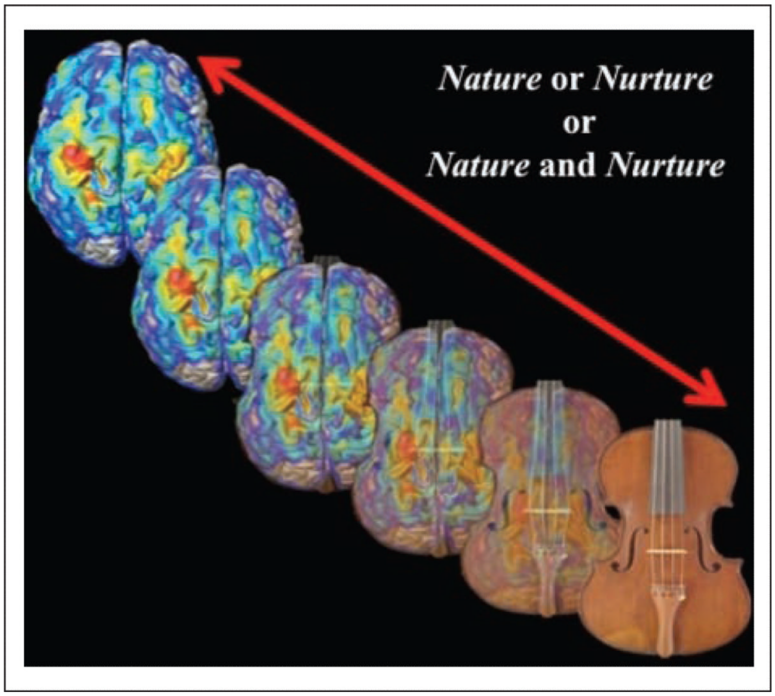

Figure 1.
Morphing a violin into a brain or a brain into a violin. Within the nature-nurture hypotheses, it is unclear in which direction the morphing goes. Does early and long-time music training lead to brain changes (nurture hypothesis), or are expert musicians born with an unusual brain (nature hypothesis) that allows them to excel at a task that requires highly specialized skills? Alternatively, do highly skilled and talented musicians have an inherent advantage by starting out with a brain anatomy that is ideal for acquiring skills that are necessary to master a musical instrument, even though the intense training changes their brains as it does for everybody else who undergoes long-term skills acquisition (nature and nurture hypothesis)? The individual brain in the upper left corner is colorized to show results of a study by Gaser and Schlaug (2003), revealing brain regions that show a positive correlation between musician status (professional musician > amateur musician > nonmusician) and increased gray matter volume. The distinction between professional and amateur musicians in this study was based on whether the keyboard player's main profession was being a musician (e.g., music teacher, performer). There was also a clear separation between both groups in terms of average practice intensity across their careers, with professional keyboard players having approximately double the amount of practice time than the group of amateur musicians (for more details, see Gaser and Schlaug 2003).

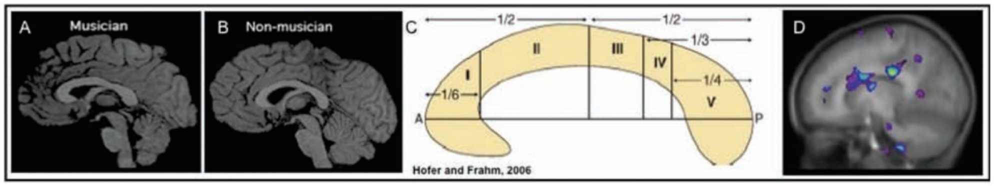

Figure 2.

Corpus callosum differences in adults (musicians v. nonmusicians) and changes over time in children. The midsagittal slice of an adult musician (A) and nonmusician (B) shows a difference in the size of the anterior and midbody of the corpus callosum (see Schlaug and others 1995a). (C) The major subdivisions of the corpus callosum and locations of the interhemispheric fibers connecting the motor hand regions on the right and left hemisphere through the corpus callosum according to a scheme used by Hofer and Frahm (2006). Reprinted with permission from Elsevier. (D) Areas of significant difference in relative voxel size over 15 months comparing instrumental ($n = 15$) versus noninstrumental control children ($n = 16$) superimposed on an average image of all children (see also Hyde and others 2009). Interestingly, most changes over time were found in the midbody portion of the corpus callosum, representing parts of the corpus callosum that contain primary sensorimotor and premotor fibers.

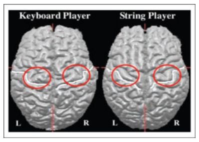

Figure 3.

Brain surface renderings of a typical keyboard and string player. The central sulcus is marked with a white line. The portion of the precentral gyrus containing the configuration similar to that of the inverted Greek letter “omega” is found within the red circles. In the 2 examples, a prominent omega sign can be seen on the left more than the right in the keyboard player and only on the right in the string player. In Bangert and Schlaug (2006), we reported significantly more prominent omega signs in the right hemisphere of string players compared to the right hemisphere of nonmusicians and more prominent omega signs in the left hemisphere of keyboard players compared to the left hemispheres of both nonmusicians and string players. Reproduced from Bangert and Schlaug 2006, with permission of Oxford University Press.

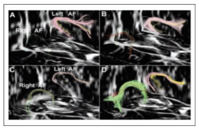

Figure 4.

Changes in the arcuate fasciculus after instrumental music training. The top row shows the right (green and red fibers represent the ventral and dorsal components of the arcuate fasciculus) and left (yellow and pink fibers represent the ventral and dorsal components of the arcuate fasciculus) arcuate fasciculus of an 8-year-old child without instrumental music training scanned twice (A and B) 2 years apart. Bottom row shows the right and left arcuate fasciculus of an 8-year-old child before (C) and 2 years after (D) instrumental music training involving a string instrument.

Figure 5.

Cerebral activation pattern of a rhythm discrimination task modulated by maturity and experience. Statistical parametric images superimposed onto a surface rendering of a standardized anatomical brain depict significant activations during a rhythmic discrimination task in a group of 5- to 7-year-old musically naïve children, adult nonmusicians, and adult musicians. The children showed prominent superior temporal gyrus activation on both sides. The adult groups show an extended pattern of activation involving polar and posterior planar regions of the superior temporal lobe as well as the parietal lobe (green circles), parts of the frontal lobe, in particular, the inferior frontal gyrus region (blue circles), and the cerebellum. Adult musicians differ from adult nonmusicians by having less activation of the primary auditory cortex but more activation of frontal regions bilaterally, particularly in the inferior frontal gyrus (blue circles). Reproduced from Bangert and Schlaug 2006, with permission of Oxford University Press.

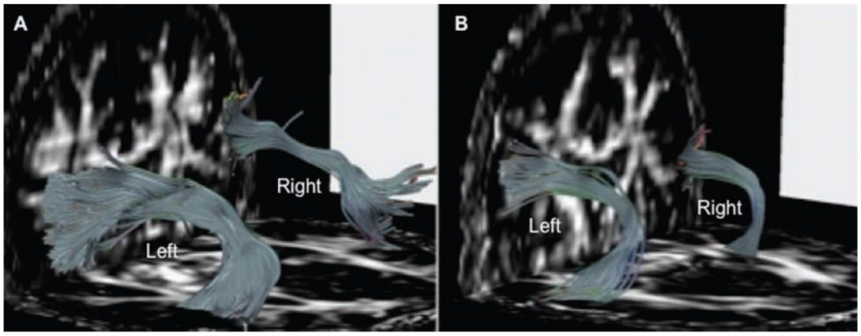

Figure 6.
The arcuate fasciculus, an auditory-motor tract, enhanced by music training. (A) The arcuate fasciculus of a healthy 65-year-old instrumental musician and (B) the arcuate fasciculus of a healthy 63-year-old nonmusician, otherwise matched with regard to their handedness, gender, and overall IQ. A comparison between both individuals shows that the musician has a larger arcuate fasciculus on the left as well as the right hemisphere than the nonmusician. Ongoing studies in our laboratory and other laboratories have shown evidence for structural plasticity of the arcuate fasciculus (Schlaug and others 2009) in individuals who undergo instrumental training or therapy using tasks that involve auditory-motor mapping, a task that musicians do throughout their life.

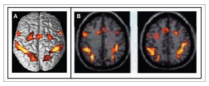

Figure 7.
Shared brain resources of a music-motor imagery task and a mental calculation task. The functional magnetic resonance image on the left (A) shows significant activations of an fMRI experiment in which subjects were asked to imagine playing scales and short music phrases with their right hand compared to a visual imagery task of 4 objects. Contrasting motor imagery (MI) with visual imagery (VI) showed bilateral activations in the superior parietal lobe as well as around the intraparietal sulcus (IPS), medial superior precuneus region, premotor region, and the supplementary motor area (SMA). Significant activations are superimposed onto a standardized brain. The functional magnetic resonance images on the right (B) show the activation pattern of a mental subtraction task in which the subtraction task was contrasted with a letter-naming task (Chochon and others 1999). It is interesting to see the similarity in the activation pattern, in particular with regard to the parietal lobe activation. Reprinted from Chochon and others 1999, with permission of MIT Press Journals.