WHAT DO MUSIC TRAINING AND MUSICAL EXPERIENCE TEACH US ABOUT BRAIN PLASTICITY?

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THIS ARTICLE SUMMARIZES THE MAIN EVIDENCE TO date regarding links between the brain and music. Musical expertise, often linked to early and intensive learning, is associated with neuroanatomical distinctive features that have been demonstrated through modern neuroimaging techniques, especially magnetic resonance imaging (MRI). These distinctive features are present in several brain regions, all more or less involved either in gestural motor skill (therefore probably related to the use of an instrument) or auditory perception. There also is growing evidence that learning music has more general effects on brain plasticity. One important notion, related to this topic, is that of a probable "sensitive period," around 7 years of age, beyond which music-induced structural changes and learning effects are less pronounced. These data are discussed in the perspective of using music training for remediation in children with specific language and reading disorders.

Received June 30, 2008, accepted October 25, 2008.

Key words: dyslexia, language, learning, music, plasticity

IT WAS NO MORE THAN 25 YEARS AGO THAT neurologists and neuroscientists started studying the musician brain, a topic that proved to be fascinating yet tremendously complex. Obviously, musicians are a very special population, not only because of their daily practice of a musical instrument (which clearly influences their brain's organization), but also because they generally begin this practice very early in their life, during childhood. Thus, musicians offer a potentially fruitful model for studying learning processes in the brain. One of the main issues we will discuss in this paper is morphological differences in the brains of professional musicians: as we shall see, knowledge about musicians' brains can provide very interesting insights on the influence of experience on cerebral morphology. The second part of this paper is devoted to the general topic of what changes in the brain when one learns music, with emphasis on recent functional imaging data obtained in children and adults while learning music. Finally, we provide a brief overview of the possible use of music training to remediate dysfunctional brains, such as those of children with language learning disorders.

The Brain of Adult Musicians: How is it Different from Nonmusicians' Brains?

Professional musicians bear two particularities that are of interest to the neuroscientist: first, musicians exert intensive and durable motor mechanisms required by the practice of their instrument, some specific to one hand or even to one or several fingers. For instance, Elbert, Pantev, Wienbruch, Rockstroh, and Taub (1995) have demonstrated enlarged cortical representation of the little finger of the left hand of violonists. Second, musicians also demonstrate more sensitive discrimination abilities for musical sounds compared to nonmusicians, with lesser specificity according to the type of instrument played (Schneider et al., 2002). These two particularities make the musician brain a fascinating experimental object for increasing our understanding of how a limited difference in learning experience can change brain structure.

Schlaug, Jancke, Huang, Staiger, & Steinmetz (1995) published one of the first papers on the influence of motor exercise on brain anatomy. The authors found that the corpus callosum—the dense bundle of white matter connecting the right and left hemispheres—was larger in musicians compared to nonmusicians, suggesting that this difference was the result of repeated, intensive sensory-motor information transfer between the right and left brain motor areas, inasmuch as learning any instrument requires tight coordination of activity across right and left hands. However, this difference only was evident if musicians started music training before the age of seven, suggesting that this effect only held during periods of intense brain plasticity. Moreover, this effect also was dependant on sexual

Music Perception VOLUME 26, ISSUE 3, PP. 279–285, ISSN 0730-7829, ELECTRONIC ISSN 1533-8312 DOI:10.1525/MP.2009.26.3.279

hormones since it only appeared in male musicians (Lee, Chen, & Schlaug, 2003).

A critical period for training influence on brain morphology also has been evidenced by asymmetry of the planum temporale. The planum temporale, a triangular surface of cortex located caudally relative to the primary auditory cortex of Heschl, is known to subserve integrative functions between different types of auditory stimuli primarily processed in Heschl's gyri. In addition, the left planum usually is larger in surface than the right one, at least in typical right-handers (Witelson & Kigar, 1992). Several studies have demonstrated that this asymmetry is modified in musicians, such that musicians show larger leftward asymmetries compared to nonmusicians (Schlaug, Jäncke, Huang, & Steinmetz, 1995; Zatorre, Belin, & Penhune, 2002). Moreover, this only held true for musicians possessing absolute (or perfect) pitch, the ability to identify or recreate a musical note without a known reference. Absolute pitch is known to appear only in musicians having started music training before age seven (Schlaug, 2001). Consequently, increased leftward asymmetry of auditory association cortex and its correlate—absolute pitch—suggest two different but related manifestations of intensive practice of an arbitrary audio-verbal association between a specific frequency and the name of the corresponding note on the musician brain. Keenan, Thangaraj, Halpern, and Schlaug (2001) demonstrated that musicians possessing absolute pitch differed from nonmusicians in the size of their right, not left, planum temporale. This finding was interpreted as evidence in favor of variations in neuronal "pruning," a process known to occur during prenatal brain development. From a different viewpoint, in a voxel-based morphometry (VBM) study (thus without the possible bias of studies looking at a specific brain region), Bermudez and Zatorre (2005) found a maximal difference in grey matter density in a small area in the lateral region of the *right* planum temporale, a region likely related to pitch discrimination. Because no differences were found between musicians who did or did not possess absolute pitch, the results suggested a shaping effect of musical experience on this part of the brain, rather than the result of predisposition. Using a similar VBM method, Gaser and Schlaug (2003) compared professional keyboard players to nonmusicians and amateur musicians. They found several regions—pertaining to both sensory-motor regions and to areas in the left anterior prefrontal lobe and the left cerebellum—of increased grey matter density in professional keyboard players compared to amateurs and nonmusicians. Since professional musicians reported approximately twice as much weekly practice time as amateur musicians, the authors suggested that the observed differences in brain morphology were direct consequences of sensory-motor experience with their instrument.

Among recent developments in brain imaging, the Diffusion Tensor Imaging (DTI) technique seems particularly well suited to music and brain research. This technique allows very fine tracing of axonal tracts coursing in the subcortical white matter, thereby offering the opportunity to follow the exact direction of the multiple connections between distant brain regions. In one such study, Schmithorst and Milke (2002) found increased fiber density and orientation (anisotropy) in the anterior callosal region, suggesting a shaping effect of intermanual activity needed for playing any instrument, but decreased anisotropy in pyramidal tracts, suggesting lesser use of corticospinal tracts due to automatization of function. Similarly, Bengtsson et al. (2005) further demonstrated that such differences in tract organization are proportional to the duration of practice (in hours per day), even in children below 11 years of age.

To summarize, the data reported above suggest that professional musicians represent a neurologically specific population, with macroscopically detectable differences in brain morphology, and that these differences concern both motor- (motor and premotor cortex, anterior CC, cerebellum) and auditory-related brain structures (Heschl's gyrus, planum temporale). Some of these differences are clearly related to musical expertise, while others are not, and most are proportional to practice duration. Specific white matter bundles, mainly pertaining to motor circuits, are better structured in musicians, including children under 11 years old. Interestingly, it seems that the anatomy of the central sulcus, situated just caudal to primary motor area, is predictive of the kind of instrument played by a given musician (Bangert & Schlaug, 2006), Specifically, the middle part of the sulcus, usually showing an omega-like curvature ('omega sign'), is more symmetrical in keyboard players, whose dexterity involves both hands equally, compared to string players, in whome the omega sign only is visible on right hemispheres. It must be noted, however, that results only showed a skewed distribution, not a clear cut dichotomy.

Learning Music: What Changes in the Brain?

As shown in the previous section, there is substantial evidence that music training results in profound and durable effects on the brain, but very little is known about what really happens in the brain during music training. Various experimental data, mainly in animals, have provided cues toward understanding the neural bases of such effects. Generally speaking, repeated practice optimizes neuronal circuits by changing the number of neurons involved, the timing of synchronization, and the number and strength of excitatory and inhibitory synaptic connections. The effects of perceptual learning have been observed in animal electrophysiology across visual, sensory, and auditory systems (Edeline, 1999; Weinberger, 2004). Anatomically, daily intensive training with sensory-motor tasks in monkeys modifies brain functional maps (Jenkins, Merzenich, & Recanzone, 1990). In the auditory modality, behaviorally trained animals exhibit increased tonotopic organization of their primary auditory cortex (Recanzone, Schreiner, & Merzenich, 1993). The mere exposure to an enriched acoustic environment without conventional training enhances auditory cortical responses and sharpens the tuning of auditory neurons, even to unfamiliar sounds in both young and old animals (Engineer et al., 2004), and such enhancements can last for days. In summary, these studies show that training and acoustic environments impact the auditory system.

Using evoked potentials, several authors have investigated functional correlates of music learning in children. Enhanced P100, N150, and P200 responses to piano tones were found in children who studied piano compared to untrained children (Shahin, Roberts, Pantev, Trainor, & Ross, 2004). Using magnetoencephalography (MEG), Pantev and colleagues (1998, 2001) found enlarged cortical representation of musical scale tones compared to pure tones in skilled musicians. Enlargement was correlated with the age at which musicians began to practice. They also investigated cortical representations for different timbres (violin and trumpet) and found that representations are preferentially enhanced in violinists and trumpeters for the timbre of the instrument on which the musician was trained.

Using functional magnetic resonance imaging (fMRI), Jäncke, Gaab, Wüstenberg, Scheich, & Heinze (2001), measured the hemodynamic responses elicited by sequences of 950 Hz pure tones (standard) and deviant tones of 952, 954, and 958 Hz before and one week after participants were trained at frequency discrimination for five sessions (over one week). Half of the participants' discrimination performance improved after training, and pre and posttraining analyses showed brain activation in a bilateral area in the superior temporal gyri, suggesting a plastic reorganization of the cortical representation for the trained frequencies.

The notion of a critical period suggests that after approximately seven years of age, music training may not have as strong and/or durable effects on anatomical representation. Watanabe, Savion-Lemieux, & Penhune, (2007) tested adult musicians—who began training before and after the age of seven—on learning of a timed motor sequence task. Results showed that early trained musicians performed better than late trained musicians, and that this performance advantage persisted after five days of practice. Performance differences were greatest on a measure of response synchronization, suggesting that early training has its greatest effect on neural systems involved in sensory-motor integration and timing. These findings support the notion of a critical period in childhood, in which enriched motor training through music practice results in long lasting benefits for performance later in life, even in nonmusical learning domains.

An interesting example of sensory-motor integration has been reported by Bangert and Altenmüller (2003), who demonstrated that 20-minutes of training in naive keyboard learners was sufficient to render durable cross-modal representations, a finding consistent with previous findings by Pascual-Leone et al. (1995). Moreover, such crossmodal sensory-motor coupling occurs even at a precognitive, unconscious level (Bangert, Jürgens, Häusler, & Altenmüller, 2006).

Recently, Fujioka, Ross, Kakigi, Pantev, & Trainor (2006) explored whether one year of music training in 4-to 6-year-old children could durably affect brain organization. The authors recorded magnetic brain potentials using MEG before and after Suzuki training. A clear music training effect was expressed in response to the violin sound via a larger and earlier N250 peak in the left hemisphere. More recently, Moreno et al. (2008) found changes in the pattern of brain waves of 8-year-old children after six months of practice, similar to results previously found in 8-year-old musicians with three to four years of music training (Magne, Schön, & Besson, 2006). Thus, while a majority of published studies compare adult musicians and nonmusicians, recent studies evaluating the first year or months of music learning in children demonstrate functional differences. Finally, Fujioka et al. (2006) found evidence of improved digit span for musically trained children and Moreno et al. (2008) demonstrated improved reading abilities of complex words and increased sensitivity to pitch changes in speech for children with music compared to painting training thereby showing transfer effects between music and nonmusical abilities.

To summarize, intensive, repetitive training through both instrument learning and auditory discrimination exercises probably shapes corresponding cortical and subcortical structures. Generally, in the case of cortical structures, this effect is demonstrated by increased surface representation. Note, however, that such functional reorganization may result from different patterns: posttraining enlargement of cortical areas suggests recruitment of more neurons, posttraining reduction suggests automatization of function, possibly relayed by subcortical structures, and posttraining shifting may reflect the use of new neural processes or the setting of new representations.

An interesting finding in this context is that of Rosenkranz, Williamon, & Rothwell (2007) who demonstrated with transcranial motor stimulation (TMS) increased brain plasticity in motor areas of musicians compared to nonmusicians.

Finally, beyond its effect on the plasticity of specific brain areas, music training, especially if started early in life, may enhance general plasticity of the brain and thus generalize to other learning domains.

Some Applications to Remediation in Learning-Impaired Children

The data described thus far offer potential for the use of music training for therapeutic purposes. Behavioral studies have shown mixed evidence for positive transfer effects between music and spatiotemporal abilities (Hetland, 2000), mathematics (Costa-Giomi, 2004), reading (Bultzlaff, 2000), speech prosody (Thompson, Schellenberg, & Husain, 2004), verbal memory (Chan, Ho, & Cheung, 1998; Ho, Cheung, & Chan, 2003) and general intelligence (Schellenberg, 2004). However, several factors (e.g., between-group differences, motivation, cognitive stimulation) often were not controlled in these experiments. In one often cited study, Chan et al. (1998) studied 60 female college students from the Chinese University of Hong Kong, of whom 30 had at least six years of training on a Western musical instrument before the age of 12, and 30 had received no music training. The two groups were matched for age (mean = 19), grade point average, and years of education. A 16-word list including words from four semantic categories was presented three times to the participants, who were asked to recall as many words as possible. On average, participants with music training recalled 16% more words than participants without music training. However, this finding may reflect specificities of tone languages (such as Thai). The specific link between music training and literacy acquisition remained poorly explored.

Musical expertise has been shown to improve several aspects of auditory processing (Peretz & Zatorre, 2005; Trainor, Shahin, & Roberts, 2003) Moreover, results of brain imaging experiments have shown that music training can improve other cognitive abilities such as digit span (Fujioka et al., 2006) and reading complex words and pitch processing in both music and speech (Moreno et al., 2008). The latter findings were taken to support growing evidence that music and speech share common processes (Besson, Schön, Moreno, Santos, & Magne, 2007; Patel, 2003). If this is indeed the case, one may assume that by improving some of the processes involved in music perception, one may also improve speech perception and reading skills. Indeed, several authors have argued that early abilities to perceive speech lay the foundation for reading skills (Gaab et al., 2005; Overy, 2003; Swan & Goswami, 1997; Tallal & Gaab, 2006). For example, Foxton et al. (2003) have demonstrated strong correlations between the ability to discriminate global pitch contour of sound sequences and phonological and reading skills in nonmusician adults. Moreover, in a large-scale study of 4- and 5-year-old children, music perception ability was shown to be predictive of reading skills (Anvari, Trainor, Woodside, & Levy, 2002). Finally, it is also interesting to note that children with reading impairments (e.g., dyslexics) showed impaired pitch discrimination performance compared to control children, and abnormal neural correlates of pitch processing (Santos, Joly-Pottuz, Moreno, Habib, & Besson, 2007).

Based on these theoretical perspectives and encouraging results, one interesting hypothesis is that music training may have particular importance in the remediation of dyslexia. However, to our knowledge, only two behavioral studies (Overy, 2003; Standley & Huges, 1997) have examined the effect of music training in children with specific language and reading learning impairments. Using a series of musical games developed for dyslexic children, focusing particularly on rhythm and timing skills, Overy (2003) engaged dyslexic children in musical activities designed to progress gradually from a very basic level to a more advanced level over a period of 15 weeks. Results showed a significant improvement, not in reading abilities, but in two related domains: phonological processing and spelling. Moreover, spelling performance was significantly correlated to results in the timing task, suggesting a link with the famous but highly debated temporal processing deficit theory of dyslexia (Tallal, 2004; Tallal & Gaab, 2006). According to this view, dyslexic children suffer from a fundamental defect in brain mechanisms devoted to processing brief and rapidly changing auditory stimuli, and this defect is at the origin of impaired phonological representation thought to cause the learning deficit characteristic of dyslexia. In a recent fMRI study (Gaab et al., 2005), 20 adult musicians and nonmusicians listened to three-tone sequences with varying interstimulus intervals (ISIs) and were asked to reproduce the order of the tones manually. Results demonstrated that music training improved behavioral performance along with a more efficient functional neural network, primarily involving classical language regions. Furthermore, performance on trials with the fastest ISI correlated significantly with the age that participants started playing a musical instrument. Based on these results, Tallal & Gaab (2006) proposed that music contains several components potentially useful for treating the temporal/phonological deficit at the origin of dyslexia.

Another aspect of music that potentially is useful for treating language/reading disorders relates to the fact that music fundamentally relies on crossmodal processing, a fact that has received considerable attention in the neuroscientific literature these last few years. For example, it has been shown that in trumpet players (Schulz, Ross, & Pantev, 2003), the pattern of brain waves recorded from the somatosensory lip area differed for combined lip and tone stimulations, and for the pattern obtained by summating responses from the unimodal lip and tone. This suggests that repeated experience with this instrument specifically developed such crossmodal abilities. Likewise, Lahav, Saltzman, and Schlaug (2003) demonstrated with functional MRI that keyboard players activated cortical regions including Broca's area when they listened to auditory melodies, but only if these melodies were in their own repertories. These results support the view that Broca's area has a role in "action listening" and that this role is compatible with that of a central "hub" in the mirror neuron network (Iacoboni et al., 1999). Finally, the notion of a brain network specifically activated in musicians by both auditory and motor activity has been documented in an fMRI study by Bangert, Peschel, et al. (2006), showing a large bilateral network coactivated by both an aural task (listening to piano melodies) and a motion-oriented task ('playing' a piano keyboard with no auditory output) in professional pianists, but not in nonmusicians. Moreover, Schneider, Schönle, Altenmüller, & Münte (2007) have demonstrated the usefulness of piano training for motor rehabilitation of stroke patients.

Such crossmodal characteristics evident in the musical brain may be particularly relevant in relation to language/reading disorders, where crossmodal deficits have been demonstrated repeatedly. This is particularly the case for the process of phoneme-grapheme mapping, which is considered a crucial problem for dyslexic children learning to read. For example, Kujala et al. (2001) found that intensive training of dyslexics with a nonlinguistic audiovisual game improved reading ability. Likewise, in French dyslexics, Magnan, Ecalle, Veuillet, & Collet (2004) and Santos et al. (2007) have used similar intensive training procedures specifically relying on audiovisual information transfer to successfully treat dyslexic children. In the latter study, authors used ERPs to demonstrate significant changes in a speech pitch discrimination task after crossmodal training, suggesting that successful treatment had drawn on common mechanisms underlying both phonology and prosody, thus encouraging the use of music in future training studies in dyslexia and related disorders.

In conclusion, the various topics addressed in this paper could easily give the impression of a heterogeneous, ungraspable scientific field, with many different facets difficult to assemble under a single theoretical construct. There are, however, considerable data that can be taken as a solid basis for future developments in this area. First, studies of the brains of musicians continue to address fundamental questions about the neurocognitive basis of music (or commonality with other cognitive processes), and more generally the role of a specific experience on the human brain. The development of brain imaging techniques promises new insights to the brain organization of both musical experts and learning students. Finally, the possibility of using music as a therapeutic tool for children struggling with learning difficulties opens fascinating avenues at the intersection of neuroscience, musicology, and pedagogy.

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