Musicians and Non-Musicians: Anatomical Differences in the Human Brain

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1 Introduction

Musicianship requires a highly sophisticated, multi-modal integration of sensory, motor, and cognitive tasks. A few of these include pitch perception, timing, musical sight-reading, composition, emotive transference, manual dexterity, remembering, and learning. These activities have been shown to activate multiple core brain regions, including the motor cortex, sensory cortex, auditory cortex, prefrontal cortex, cerebellum, visual cortex, corpus callosum, hippocampus, nucleus accumbens, amygdala, and cerebellum (Levitin and Tirovolas, 2009). Table 1 shows common musical activities that core brain regions have been associated with. There are few human activities as permeative as musicianship that recruit as many areas of the brain. This fact has prompted researchers to ask the question,"Is a musical brain different from a non-musical brain?" In the last decade and a half, new technologies allowing accurate spatial and temporal brain imaging have propelled an explosion of such research.

The fundamental question of brain difference between musicians and non-musicians can be approached in two primary ways. The first is to study brain function, or whether the brain reacts to a stimulus in a particular fashion. The second is to study the structure of the brain, or whether the shape, size, density, or volume of key regions differ between certain groups of people. This paper provides a summary overview of research on the anatomical brain differences between musicians and non-musicians.

This report is roughly sectioned by brain region. The planum temporale (Section 2); corpus callosum (Section 3); primary motor cortex (Section 4); cerebellum (Section 5); and Heschl's gyrus (Section 6) are each discussed with respect to morphometric differences between musicians and non-musicians. The studies covered here use Magnetic Resonance (MR) imaging techniques to discover surface area or volume measurements. Most of these are focused on particular "regions of interest" in the brain. Recent technology has allowed more comprehensive examination of the brain by voxel-based morphometrics and other methods, though. Some of these studies are summarized in Section 7. A brief conclusion sums up the findings presented in this paper (Section 8). Figure 1 shows the relative locations of most brain areas that are discussed in this paper.

2 Planum Temporale

The planum temporale (PT) is located just near the auditory cortex, posterior to Herschl's gyrus and in the center of Wernicke's area (Levitin and Tirovolas, 2009). It is often referred to as a "computational hub" responsible for disambiguating sounds, and it has been associated with music perception (Zatorre et al., 2007). The PT has been found to be a highly lateralized region in the brain, correlating closely with handedness, and shown to be a marker of structural and functional asymmetry.

Three studies have shown increased leftward asymmetry between musicians with absolute pitch (AP) and non-musicans, however with sightly different results. In one study, a significant leftward surface area asymmetry was found in musicians with AP (Schlaug et al., 1995) versus musicians with relative pitch (RP). No significant difference was found between RP musicians and non-musicians. Volumetric asymmetry was confirmed in (Zatorre et al., 1998), however in this study a significant difference was found between musicians with AP and musicians with RP. It was also remarked that an overall increase in size of the PT was observed for AP musicians, and that leftward asymmetry shouldn't be overemphasized. Leftward asymmetry of AP musicians was confirmed again in a third (surface area) experiment (Keenan et al., 2001), but asymmetry was found to be the result of a diminished right PT, rather than any significant contribution by the left hemisphere. The results from these studies, taken together, highlight the difficulty inherent in interpreting and comparing MR images.

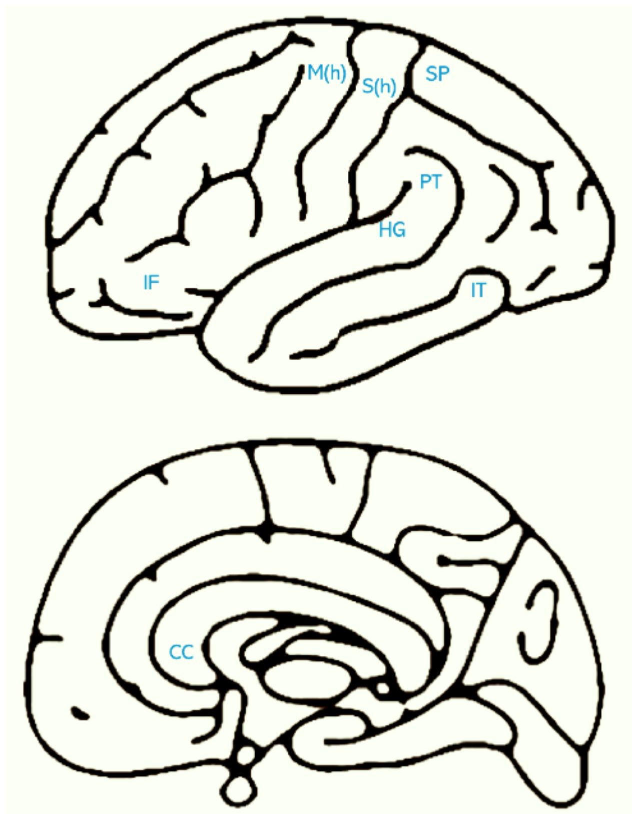

Figure 1: A schematic representation showing regions of specialization in the brains of musicians. CC = corpus callosum; HG = Heschl's gyrus (site of primary auditory cortex); IF = inferior frontal cortex; IT = inferior temporal cortex; M(h) = hand area of motor cortex; PT = planum temporale; S(h) = hand area of somatosensory cortex; SP = superior parietal cortex (Stewart, 2008).

Core Brain Region	**Musical Activity**
Motor Cortex	Movement, foot-tapping, dancing, and playing an instrument
Sensory Cortex	Tactile feedback from playing an instrument and dancing
Auditory Cortex	The first stages of listening to sounds, the perception and analysis of tones
Prefrontal Cortex	Creation of expectations; violation and satisfaction of expectations
Cerebellum	Movement such as foot-tapping, dancing, and playing an instrument. Also involved in emotional reactions to music
Visual Cortex	Reading music, looking at a performer's music (including one's own)
Corpus Callosum	Conects left and right hemispheres
Hippocampus	Memory for music, musical experiences, and contexts
Nucleus Accumbens	Emotional reactions to music
Amygdala	Emotional reactions to music
Cerebellum	Movement such as foot-tapping, dancing, and playing an instrument. Also involved in emotional reactions to music

Table 1: Core brain regions associated with musical activity (Levitin and Tirovolas, 2009).

A separate study tested for differences in metabolite concentrations in the PT by performing quantitative proton MR spectroscopy (Aydin et al., 2005). Comparisons of ten musicians with age- and sex-matched non-musicians determined a statistically significant difference in N-acetylaspartate concentrations between the two groups, with no difference in choline or creatine concentrations. While the exact function of NAA is not known, the authors argue that metabolite concentrations my be a more sensitive indicator of cellular change and brain adaptation than MR imaging.

3 Corpus Callosum

The corpus callosum (CC) lies longitudinally underneath the cortex, connecting the hemispheres of the brain. Several reasons make it an interesting structure for study. Its structural and functional maturation extends into late childhood and early adolescence; human movement and motor control generally improves coincidentally with CC maturation; and its midsagittal area correlates positively with the the number of interhemispheric fibers crossing through the CC (Schlaug, 2001).

Schlaug et al. (1995) have shown significant differences in the surface area of the anterior half of the CC between several groups of subjects. All musicians have more CC surface area than non-musicians and musicians that commence training at an early age ($\leq$ 7 years old) exhibit larger CC size than musician who commenced musical training at a later age. These results suggest that CC size is adaptive during maturation and grows larger for musicians who necessitate increased interhemispheric communication for complex bimanual movements.

In an important extension to the previous study, Lee et al. (2003) found sexually dimorphic trends in CC size. While previous results between male musicians and non-musicians were replicated, female musicians exhibited no significant difference in CC surface area, compared to female non-musicians. This gender difference is possibly explained by the fact that females exhibit lesser general lateralization than males, placing a lower demand for increased CC size, and therefor interhemispheral communication.

4 Primary Motor Cortex

The primary motor cortex (PMC) is located on the precentral gyrus. This region, responsible for planning and executing motor movements, is abutted by the central sulcus, which separates it from the somatosensory cortex. It is theorized that musicians such as piano players or keyboard players who effectuate complex hand movements depend heavily on this part of the brain.

To test this theory, Amunts et al. (1997) conducted an experiment to measure if the PMC's size was different for keyboard players and string players, whose respective practices require consistent and articulate bimanual and unimanual control of the fingers, than for non-musicians. As the histological extent of the PMC is difficult to define, they used gross anatomical markers for measurement; the intrasulcal length of the precentral gyrus (ILPG) along the posterior wall was compared. They found that, while no significant differences were established between string and piano players, musicians exhibited less leftward asymmetry in ILPG than non-musicians. Additionally, ILPG was correlated positively with the age that musical training commenced. They posit that these findings suggest brain plasticity to long-term motor demands. However, these findings cannot eliminate the possibility that humans with a lesser ILPG asymmetry have a higher tendency to become musicians.

These findings were extended when course visual inspections of the Omega Sign (OS) of the precentral sulcus for keyboard players, string players, and non-musicians were compared (Bangert and Schlaug, 2006). The OS is an anatomical landmark associated with hand movement. VIsual inspections of the OS showed with statistical significancy that piano players had a leftward and string players a rightward asymmetry in OS expression compared with non-musicians, suggesting adaptation at the musician's brain level to type of instrument.

5 Cerebellum

Located in the inferior posterior portion of the head, the cerebellum is responsible for a complicated amalgamation of functions, many to do with timing. There are a number of outstanding theories for the cerebellum's role. The cerebellum may be involved in feed-forward control or error correction of movements; it my compute predictive models of movement; or it may be important for online correction of movements based on feedback. It has been theorized that the cerebellum is engaged in precision control of trajectory movements, and that it is connected to the acquisition and integration of sensory information. The cerebellum has also been implicated in production and learning of motor sequences. Whatever the case, surmounting functional evidence suggests that the cerebellum plays a large factor in timing (Zatorre et al., 2007).

Hutchinson et al. (2003) studied cerebellar volume of musicians and non-musicians. They found that actual and relative (to total brain volume) cerebellar volume of male musicians was significantly greater than non-musicians; there was no significant difference in total brain volume between the two groups. Correlation of relative cerebellar volume to three other factors was computed—average intensity of practice throughout life, age of commencement of training, and years of training. A significant (positive) correlation was found for only the first factor. In their discussion, Hutchinson et al. suggest that the cerebellum's function in motor and non-motor error correction becomes significantly important as practice intensity increases, and is reflected in male musicians' relatively enlarged cerebellums.

Interestingly, no significant effect of musicianship on cerebellar volume was found in the female group, but there was a significantly larger relative cerebellar volume for females than males. This is largely accounted by females having similar cerebral volumes as males, but smaller total brain volumes than males. No strong conclusions can be drawn as to what this means in terms of musicianship. It is postulated that, as females reach cerebellar maturation earlier than males, long-term musicianship effects may be distributed to outside of the cerebellum in females.

6 Heschl's Gyrus

Heschl's gyrus (HG) is also known as the transverse temporal gyrus. Together, with the superior temporal gyrus, it contains the primary auditory cortex and Brodmann areas 41 and 42. HG has been noted for its importance in the processing of musical tones and intervals (Levitin and Tirovolas, 2009).

Schneider et al. (2002) functionally and anatomically analyzed the HG in 37 subjects consisting of professional musicians, amateur musicians, and non-musicians. First, a functional response was evoked by pure and amplitude modulated tones and measured by magnetoencephalography (MEG). The measured MEG amplitudes were correlated to a musical aptitude test. A partial correlation was then calculated between that and HG morphometry. They found that the anterior portion of HG was 37% greater and the anteromedial portion was 130% greater in volume for musicians than non-musicians.

In a second study, the morphometry of the HGs of subjects made up of 125 professional orchestral musicians, 181 graduate students in music, 66 amateur musicians, and 48 non-musicians were studied (Schneider et al., 2005). The subject pool was dichotomized by a perceptual pitch-shift listening task. Subjects were asked to judge the direction of pitch shift of pairs complex tones; the tones were synthetically shifted by either fundamental frequency (f_0) alone, or by spectral harmonics (f_{SP}) alone, and subjects were asked which direction they perceived a shift in. Responses were bimodal across the pool of subjects, and subjects were grouped into f_0 and f_{SP} categories based upon their average ratings. Morphometry revealed that the two groups predicted cortical gray matter asymmetry for the lateral HG. A left hemispheric specialization was found for f_{SP} subjects and the opposite was shown for f_0 subjects. These results were irrespective of musical aptitude, suggesting that brain anatomy can predict low-level pitch-processing specialization in individuals.

7 Panoptic Studies

Traditional neuro-imaging techniques usually examine the surface area or volume of the brain by drawing regions of interest and examining their broader characteristics. Voxel-based morphometry allows closer examination of the brain against other brains and itself by registering it to a template (Ashburner and Friston, 2000). There have been a number of recent studies that have used such techniques to take a more global structural view of the brain, at times with a specific subject group or brain region in mind. A few of these are reviewed below, beginning with a study that didn't target any specific part of the brain or musical subclass; an additional study using a different method, diffusion tensor imaging, is also included.

7.1 Global

In an attempt to corroborate previous morphometric studies and at the same time trace new anatomic connections to musician status, Gaser and Schlaug (2003) studied voxel-based morphometrics of the entire brain for professional musicians, amateur musicians, and non-musicians. Their findings agreed with previous studies; increase in gray matter volume was found in the primary motor and somatosensory areas, premotor areas, left cerebellum, and left HG for professional musicians (and to a lesser extent amateur musicians). Of interest were new findings in positive correlation between gray matter volume in the anterior superior parietal areas and the inferior temporal gyrus. The superior parietal region has been found to play an important role in integrating multimodal sensory information and providing guidance for motor operations—tasks fundamental to music playing. It has also been shown to be important for musical sight-reading. The inferior temporal gyrus includes regions involved in the ventral visual stream, which has been functionally associated with learning to choose actions prompted by visual stimuli. Again, these are tasks that musicians are frequently engaged in, especially when watching others perform.

The study revealed no significant volumetric differences in the PT between musicians and non-musicians, in accord with earlier studies (Schlaug et al., 1995; Keenan et al., 2001). No difference in white matter was found between groups as well, but the authors speculate that this is more likely a result of a deficit in the techniques they used in the voxel-based morphometry, and not to be taken as substantive evidence of a lack of difference.

A global examination of cortical thickness and voxel-based morphometry was undertaken by Bermudez et al. (2008) to compare less homogenous populations of AP musicians, RP musicians, and non-musicians. Their findings corroborated many previous ones, but also brought some new information to the surface. They show evidence that the lateral portion of HG and other areas lying outside the primary auditory cortex along the superior temporal gyrus have an increased cortical thickness, possibly representing a significant impact on pitch perception. And they observe several areas of decreased cortical thickness in AP musicians compared to RP musicians; these were located in the posterior dorsal frontal cortexes, which have been shown to be important in conditional associative memory.

7.2 Symphony Orchestra Musicians

Sluming et al. (2002) employed voxel-based morphometry with the hypothesis that orchestral musicians would exhibit enlarged gray matter in Broca's area, which has been linked to spoken language, visuospatial, and audiospatial localization. Because musical scores are arranged in a spatially systematic manner and because musicians are required to sight-read or interpret spatially-oriented symbols efficiently, the authors believed they would find a positive association with Broca's area. 26 orchestra musicians were compared with 26 non-musicians, and morphometric results affirmed their hypothesis. Additionally, they found a statistically significant negative correlation between age and non-musicians; older subjects had decreased gray matter volume in Broca's area compared to musicians. The authors suggest that the demands of sight-reading activity might mitigate age-related atrophy of that area in the brain.

7.3 Subjects with Amusia

Congenital amusia is a developmental disorder which affects approximately 4% of the human population, preventing individuals from perceiving musical features, such as relative pitch. Hyde et al. (2006) set about to find, by voxel-based morphometry, whether white matter volume could be correlated with amusia—specifically in the pitch-processing region of the brain—but also more generally. A significantly negative correlation between white matter volume and amusic subjects was established in two independent studies. Specifically, the right inferior frontal gyrus, an area previously implicated in pitch memory, of amusic subjects was found to be abnormally deficient in white matter.

Conversely, the authors observed a larger than normal volume of gray matter in the same reasons. they measured cortical thickness in the white matter deficient areas of amusic and normal individuals (Hyde et al., 2007). As predicted, they found morphological anamolies in cortical thickness in the inferior frontal gyrus for amusic subjects. It was not possible to determine whether white matter deficiency or extended cortical thickness was responsible for amusia.

7.4 Fiber Tract Organization

(Bengtsson et al., 2005) used diffusion tensor imaging to determine if a link could be established between volume of white matter and musicianship, as well as age of commencement of musical training. In humans, some central fiber tracts continue to mature past thirty years of age; white matter volume might therefor exhibit higher correlation to musical training at later years of life than gray matter. In their study, the authors discovered that white matter volume could only be significantly linked to musicians in one area: the right posterior internal capsule. However, multiple regions of significance were established when practicing time was considered with respect to children of different age groups. The authors believe these results suggest that training can induce white matter plasticity if it occurs when the fiber tracts are not fully maturated.

7.5 Children

A longitudinal study of children without prior musical training was conducted to determine the structural impact of music training (Hyde et al., 2009). In particular, brain deformation changes were tracked over a 15 month period, in one month intervals, between children who received musical training and those who did not. The average age of children at the start of the experiment was approximately 6 years, and there were no significant differences in brain structure between the two groups at the start of the experiment. Brain deformations were observed in the frontal, temporal, and parieto-occipital brain areas during the extent of the study. Between-group differences revealed areas of greater relative voxel size in motor areas and right primary auditory regions of “instrumental” children compared to controls. These findings indicate that musical training can lead to divergent structural brain changes in musically trained children versus children who don’t receive musical training.

8 Conclusion

This paper has presented a number of studies on the relative differences of musicians and non-musicians in structural brain anatomy. Overwhelming evidence shows that musician brains are structurally different than non-musician brains. Many differences can be correlated with age of commencement for musical training, intensity of training, or, number of years of training. Furthermore, many regions of the brain exhibit plasticity—the brain can adapt to fit the heightened demands that increased musicianship places. But plasticity has shown to generally be greater at younger ages, especially for areas that are not fully matured.

There is an ongoing debate as to whether structural features of musician brains are solely a reflection of brain plasticity and adaptation or whether innate parameters draw people with "musical" brains into musicianship. While the alternative hypothesis is difficult to prove untrue, most researchers speculate that most brain adaptations are a direct result of training, rather than innateness. The final study reviewed in this paper, (Hyde et al., 2009), comes the closest to proving the alternative hypothesis as invalid. The innateness of the musical brain promises to be an active and growing area of research in the immediate future.

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Note: For citations on local brain function, reference is often given to papers which provide summary information, not to the original works which publish such findings.