

STRUCTURAL BRAIN DIFFERENCES BETWEEN MUSICIANS AND NON-MUSICIANS

Christian Gaser^{1,2}

Gottfried Schlaug¹

¹ Dept. of Neurology, Neuroimaging and Music Laboratory,
Beth Israel Deaconess Medical Center and Harvard Medical School, Boston, USA

² Dept. of Psychiatry, University of Jena, Germany

ABSTRACT

Musicians learn complex motor and auditory skills at an early age and practice these specialized skills - such as translating visually presented musical symbols into motor commands with auditory monitoring - extensively from childhood through their entire careers. Using a voxel-by-voxel morphometric technique, we found gray matter volume differences in motor as well as auditory and visual-spatial brain regions comparing professional musicians (keyboard players) with matched amateur musicians and non-musicians. These multi-regional differences might represent structural adaptations in response to long-term skill learning and repetitive rehearsal of these skills. This is supported by finding a strong association between structural differences, musician status, and practice intensity, as well as by a wealth of supporting animal data showing structural changes in response to long-term motor training.

1. INTRODUCTION

Musicians are skilled in performing complex physical and mental operations such as translating visually presented musical symbols into complicated movements of fingers and hands, and memorizing long musical phrases. Playing a musical instrument typically requires the integration of multimodal sensory and motor information and multimodal sensory feedback mechanisms to monitor the performance. Several behavioral, neurophysiological, and neuroimaging studies have explored these exceptional and specialized skills of musicians. Nevertheless, the neural correlates of most musical operations are not fully understood. There is very preliminary data from various groups to establish an association between specialized musical skills and particular brain regions or a characteristic brain anatomy. Several functional imaging studies have shown differences between musicians and non-musicians while performing motor, auditory or somatosensory tasks (Elbert et al., 1995; Pantev et al., 1998; Schlaug, 2001). Similarly, structural brain differences between musicians and non-musicians were reported in a few a priori defined motor and auditory brain regions (Amunts, 1997; Schlaug et al., 1995b; Schlaug et al., 1995a; Schlaug, 2001; Zatorre et al., 1998). However, no study has yet searched across the whole brain space for structural differences between musicians and non-musicians that could be linked to the exceptional and specialized skills of musicians as well as the long-term and extensive rehearsal of these skills.

We applied an optimized method of voxel-based morphometry (VBM) (Ashburner and Friston, 2000; Good et al., 2001) to explore whether structural brain differences exist between three

groups of subjects which differed with regard to their musician status and practice intensity: professional musicians, a matched group of amateur musicians, and a matched group of non-musicians.

2. METHODS

Subjects. We compared 20 male professional musicians and 20 male amateur musicians (all keyboard players) to a group of 40 male non-musicians (all matched with regard to age, handedness, and verbal skills). A professional musician was defined as someone whose main profession is to be a musician (either a performing artist, music teacher or music student at a conservatory) with an average practice time of at least 1 hour per day. An amateur musician was defined as someone who plays a musical instrument regularly but has a profession other than being a professional musician. The amateur musicians had an average daily practice time that was half that of professional musician (1.15 hrs/d vs 2.23 hrs/d). Non-musicians were defined as those who never played a musical instrument.

MR Data Acquisition and Image Analysis. We used magnetic resonance imaging (MRI) to acquire high-resolution anatomical images (voxel size 1mm³) of the whole brain. Images were acquired on a 1.5 Tesla Siemens Vision whole-body scanner (Erlangen, Germany) using a MPRAGE sequence. These images were then analyzed with a fully automatic technique for computational analysis of differences in local gray matter volume - VBM. This method involves the following steps: (i) spatial normalization of all images to a standardized anatomical space by removing differences in overall size, position, and global shape; (ii) extracting gray matter from the normalized images; and (iii) analyzing differences in local gray matter volume across the whole brain (Ashburner and Friston, 2000). To analyze our structural data we applied an optimized method of VBM (Ashburner and Friston, 2000; Good et al., 2001) using the SPM99 package (Institute of Neurology, London, UK). The spatial normalization to the standard anatomical space was performed in a two-stage process. In the first step we registered each image to the International Consortium for Brain Mapping (ICBM) template (Montreal Neurological Institute, Montreal, Canada), which approximates Talairach space. We applied a 12-parameter affine transformation to correct for image size and position. Regional volumes were preserved while correcting for global differences in whole brain volume. The normalized images of the control subjects only were averaged and smoothed with a Gaussian kernel of 8 mm full-width at half-maximum (FWHM) and then used as a new template with reduced scanner- and population-specific bias. In the second normalization step, we

locally deformed each image of our entire group to the new template using a non-linear spatial transformation. This accounts for the remaining shape differences between the images and the template and improves the overlap of corresponding anatomical structures. Finally, normalized images were corrected for non-uniformities in signal intensity and partitioned into gray and white matter, cerebrospinal fluid, and background using a modified mixture model cluster analysis. In order to remove unconnected non-brain voxel (e.g., rims between brain surface and meninges), we applied a series of morphological erosions and dilations to the segmented images (Good et al., 2001). The resulting gray matter images were smoothed with a Gaussian kernel of 12 mm FWHM. Voxel-by-voxel t-tests using the general linear model were used to search for gray matter differences between professional musicians, amateur musicians, and non-musicians. We assessed the correlation between musician status and gray matter differences by modeling the musician status as a 3-level gradation, in which professional musicians were highest and were assigned a value of 1, amateur musicians were intermediate and were assigned a value of 0.5, and non-musicians were the lowest and assigned a value of 0.

All voxels with a gray-matter volume value below 0.2 (of a maximum value of 1) were excluded from the analysis to include only voxels with sufficient gray matter portion. All statistical images were thresholded at $P < 0.05$ and corrected for multiple comparisons. Only clusters with a minimum number of 225 voxel are reported which corresponds to a spatial extent threshold of $P < 0.1$.

3. RESULTS

Areas of significantly increased gray matter volume comparing professional musicians (keyboard players) with amateur musicians (keyboard players) and non-musicians were found in peri-rolandic regions including primary motor and somatosensory areas, premotor regions, superior parietal regions, and the inferior temporal gyrus bilaterally (Fig. 1).

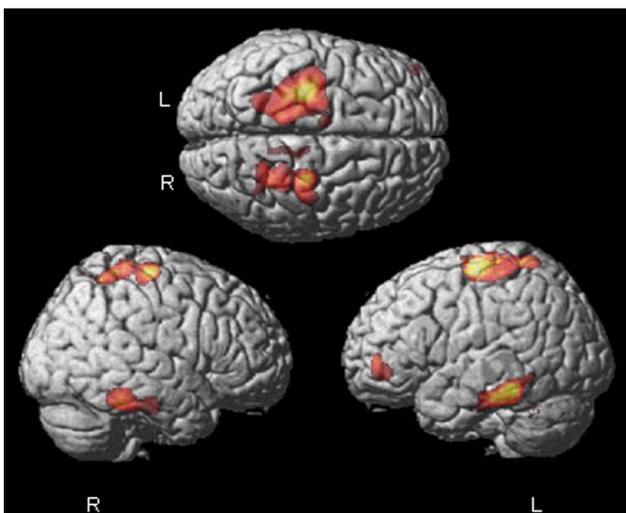


Figure 1: Brain regions with gray matter differences between professional musicians, amateur musicians, and non-musicians ($P < 0.05$, corrected for multiple comparisons, only clusters of voxels consisting of at least 225 voxels are displayed corresponding to a spatial extent threshold of $P < 0.1$).

Additional differences were seen in the left cerebellum, left Heschl's gyrus, and left inferior frontal gyrus. There were no areas showing a significant decrease in gray matter volume comparing professional with amateur musicians and amateur musicians with non-musicians, respectively. These results partly corroborate and greatly expand upon our earlier data obtained with traditional morphometric techniques in a priori defined anatomical regions, which showed differences in a marker of primary motor cortex size and cerebellar volume between musicians and non-musicians (Amunts, 1997; Schlaug, 2001).

4. CONCLUSIONS

Our results suggest a pattern of differences in the gray matter distribution between professional musicians, amateur musicians, and non-musicians that involves motor, auditory, and visual regions. Motor related regions such as the premotor and cerebellar cortex have been shown to play a critical role in the planning, preparation, execution, and control of bimanual sequential finger movements. Furthermore, functional changes in the movement representation pattern have been demonstrated during motor learning in these regions. The location of cerebellar gray matter differences in our study corresponds to the area of the cerebellar finger/hand representation as determined by functional imaging studies. Furthermore, the cerebellum has also been implicated in cognitive skill learning as well as music processing. These aspects of music training could also contribute to the structural differences in the cerebellum. The structural differences in the left Heschl's gyrus (Fig. 1) support results of a recent study showing higher gray matter volume in this region in musicians, which was associated with neurophysiological source activity differences between professional musicians, amateur musicians, and non-musicians while listening to tones (Schneider et al., 2002).

The superior parietal region may be a crucial center for integrating multimodal sensory information (e.g., visual, auditory, and somatosensory) and for providing guidance to motor operations through intense reciprocal connections with the premotor cortex. Its important role in musical sight-reading, a task that would heavily rely on the fast integration of multimodal sensory information and motor preparation, was shown in a previous study (Sergent et al., 1992). Musicians practice this visual-spatial to motor transformation repetitively for their entire professional career, with immediate auditory feedback which aids in matching the visual patterns with the motor program.

Our study also showed strong differences between the two musician groups and the non-musicians in the inferior temporal gyrus, most probably including anatomical regions involved in the ventral visual stream. The interpretation of this result is aided by functional neuroimaging studies that have shown learning-related activity increases in the inferotemporal cortex and associated changes in the ventral prefrontal cortex to which the inferotemporal cortex projects when subjects learn to choose actions according to a visual stimulus (Passingham and Toni, 2001), a process that musicians are continuously engaged in when they play their instrument.

Overall, the results of our study and other studies (Elbert et al., 1995; Keenan et al., 2001; Pantev et al., 2001; Schneider et al., 2002; Zatorre et al., 1998) provide strong links between specialized skills and certain brain structures. Neural plasticity may allow use-dependent regional growth and structural

adaptation in cerebral gray matter in humans in response to intense environmental demands during a critical period of brain maturation, similar to what has been described in animal studies (Anderson et al., 1994; Anderson et al., 2002; Black et al., 1990; Isaacs et al., 1992; Kleim et al., 1996; Zheng and Purves, 1995; Zilles, 1992). The strong association between gray matter differences and musician status in our study lends further support to the proposal that the brains of musicians might show use-dependent structural changes. Amateur musicians showed an intermediate increase in gray matter volume in comparison to non-musicians and professional musicians. Further support for the proposal of structural plasticity comes from animal experiments showing micro-structural changes in the cerebellum, primary motor cortex, and hippocampus that are related to motor skill learning and continuous motor activity (Anderson et al., 1994). Compared to a voluntary exercise control group, acrobatic motor training in rats resulted in an increase in the number of synapses per neuron and a greater number of glial cells and glial volume per Purkinje cell in the cerebellar cortex. The forced routine exercise group had a predominant increase in capillary density, as well as smaller changes in synapse and glial cell density. The sum of these microstructural changes has been reported to lead to volume differences detectable on a macroscopic level in several animal experiments (Anderson et al., 1994; Anderson et al., 2002; Passingham and Toni, 2001; Pysh and Weiss, 1979).

Alternatively, it is also possible that extremes or particular patterns of normal anatomical variability foster the development of extraordinary abilities, in which case such special anatomy would be a prerequisite for advanced skill acquisition rather than its consequence. If these structural differences are innate, individuals exhibiting such differences in brain anatomy might be drawn to becoming musicians and may face fewer obstacles in mastering a musical instrument, because they are equipped with the necessary brain anatomy. Although self-selection for musicianship by individuals with innate extraordinary brain development cannot be completely ruled out, the strong relationship between structural differences and musician status and practice intensity - and a wealth of supporting data from animal experiments examining structural brain effects of skill acquisition and long-term motor training - would support the proposal that volumetric structural differences seen in musicians might be adaptations to long term musical training. Furthermore, finding differences between musicians and non-musicians in several anatomically distinct brain regions makes it less likely that these differences are innate or may determine whether someone succeeds in becoming a musician. The results of our study establish a base for future studies probing more directly causal relationships between long-term training and related structural changes in specific brain regions.

5. REFERENCES

1. Amunts, K. (1997). Motor cortex and hand motor skills: Structural compliance in the human brain. *Human Brain Mapping* **5**, 206-215.
2. Anderson, B.J., Eckburg, P.B., and Relucio, K.I. (2002). Alterations in the thickness of motor cortical subregions after motor-skill learning and exercise. *Learn. Mem.* **9**, 1-9.
3. Anderson, B.J., Li, X., Alcantara, A.A., Isaacs, K.R., Black, J.E., and Greenough, W.T. (1994). Glial hypertrophy is associated with synaptogenesis following motor-skill learning, but not with angiogenesis following exercise. *Glia* **11**, 73-80.
4. Ashburner, J. and Friston, K.J. (2000). Voxel-based morphometry--the methods. *Neuroimage*. **11**, 805-821.
5. Black, J.E., Isaacs, K.R., Anderson, B.J., Alcantara, A.A., and Greenough, W.T. (1990). Learning causes synaptogenesis, whereas motor activity causes angiogenesis, in cerebellar cortex of adult rats. *Proc. Natl. Acad. Sci. U. S. A* **87**, 5568-5572.
6. Elbert, T., Pantev, C., Wienbruch, C., Rockstroh, B., and Taub, E. (1995). Increased cortical representation of the fingers of the left hand in string players. *Science* **270**, 305-307.
7. Good, C.D., Johnsruide, I.S., Ashburner, J., Henson, R.N., Friston, K.J., and Frackowiak, R.S. (2001). A voxel-based morphometric study of ageing in 465 normal adult human brains. *Neuroimage*. **14**, 21-36.
8. Isaacs, K.R., Anderson, B.J., Alcantara, A.A., Black, J.E., and Greenough, W.T. (1992). Exercise and the brain: angiogenesis in the adult rat cerebellum after vigorous physical activity and motor skill learning. *J. Cereb. Blood Flow Metab* **12**, 110-119.
9. Keenan, J.P., Thangaraj, V., Halpern, A.R., and Schlaug, G. (2001). Absolute pitch and planum temporale. *Neuroimage*. **14**, 1402-1408.
10. Kleim, J.A., Lussnig, E., Schwarz, E.R., Comery, T.A., and Greenough, W.T. (1996). Synaptogenesis and Fos expression in the motor cortex of the adult rat after motor skill learning. *J. Neurosci.* **16**, 4529-4535.
11. Pantev, C., Oostenveld, R., Engelien, A., Ross, B., Roberts, L.E., and Hoke, M. (1998). Increased auditory cortical representation in musicians. *Nature* **392**, 811-814.
12. Pantev, C., Roberts, L.E., Schulz, M., Engelien, A., and Ross, B. (2001). Timbre-specific enhancement of auditory cortical representations in musicians. *Neuroreport* **12**, 169-174.

13. Passingham, R.E. and Toni, I. (2001). Contrasting the dorsal and ventral visual systems: guidance of movement versus decision making. *Neuroimage*. **14**, S125-S131.
14. Pysh, J.J. and Weiss, G.M. (1979). Exercise during development induces an increase in Purkinje cell dendritic tree size. *Science* **206**, 230-232.
15. Schlaug, G. (2001). The brain of musicians. A model for functional and structural adaptation. *Ann. N. Y. Acad. Sci.* **930**, 281-299.
16. Schlaug, G., Jancke, L., Huang, Y., Staiger, J.F., and Steinmetz, H. (1995a). Increased corpus callosum size in musicians. *Neuropsychologia* **33**, 1047-1055.
17. Schlaug, G., Jancke, L., Huang, Y., and Steinmetz, H. (1995b). In vivo evidence of structural brain asymmetry in musicians. *Science* **267**, 699-701.
18. Schneider, P., Scherg, M., Dosch, H.G., Specht, H.J., Gutschalk, A., and Rupp, A. (2002). Morphology of Heschl's gyrus reflects enhanced activation in the auditory cortex of musicians. *Nat. Neurosci.* **5**, 688-694.
19. Sergent, J., Zuck, E., Terriah, S., and MacDonald, B. (1992). Distributed neural network underlying musical sight-reading and keyboard performance. *Science* **257**, 106-109.
20. Zatorre, R.J., Perry, D.W., Beckett, C.A., Westbury, C.F., and Evans, A.C. (1998). Functional anatomy of musical processing in listeners with absolute pitch and relative pitch. *Proc. Natl. Acad. Sci. U. S. A* **95**, 3172-3177.
21. Zheng, D. and Purves, D. (1995). Effects of increased neural activity on brain growth. *Proc. Natl. Acad. Sci. U. S. A* **92**, 1802-1806.
22. Zilles, K. (1992). Neuronal plasticity as an adaptive property of the central nervous system. *Anat. Anz.* **174**, 383-391.