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Differences in white matter architecture between musicians and non-musicians: a diffusion tensor imaging study

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Abstract

Previous studies found structural brain differences between musicians and non-musicians. In order to determine possible differences in white matter architecture, diffusion tensor imaging was performed on five adult subjects with musical training since early childhood, and seven adult controls. The musicians displayed significantly greater fractional anisotropy (FA) in the genu of the corpus callosum, while significantly less FA was found in the corona radiata and the internal capsule bilaterally. Further areas also showed significant differences. We hypothesize that these changes are due to the cognitive and motor effects, respectively, of musical training.

Keywords: Musical training; Diffusion tensor imaging; White matter architecture; Fractional anisotropy

Previous studies have found differences in anatomical brain structure between musicians and non-musicians. The anterior part of the corpus callosum has been found to be larger in musicians [13], while the leftward asymmetry in the planum temporale has been found to be larger only in musicians with perfect pitch [14,18]. Also, the cortical representation of the much-used left hand was found to be greater in string players than in controls [5].

We investigate possible differences in diffusion properties between non-musicians and subjects with continuous musical training during early childhood and adolescence. A previous study [16] showed increases in diffusion anisotropy with age throughout childhood, especially in the corticospinal tract. Musical training involves the development of repetitive fine motor skills as well as other cognitive processes, and an ongoing maturation of brain structures and their connecting pathways is essential for the continuing development of both cognitive and motor functions [1]. The criterion of continuous musical training throughout childhood and adolescence is used since significant changes in white matter diffusion properties occur throughout the developmental period [16], and emotional perception in music appears to be highly developed early on in childhood [3]. Thus, our hypothesis was that significant differences in white matter architecture would be apparent between the two groups.

The fractional anisotropy (FA) indicates the degree of directionality of water diffusion and has a range of zero, in the case of completely isotropic diffusion, to one, in the case of completely anisotropic diffusion. In white matter, water diffuses more easily along axons than perpendicular to them, and increased organization of white matter tracks will be reflected in increased FA values. The FA may thus be seen as an indicator of white matter organization on a microstructural level, which is not readily assessable by other means in vivo. The highest FA values are found in the internal capsule, where many parallel fibers in a tight space require a high degree of organization [16].

Eleven normal adults participated in the study. Five subjects (mean age 31.2 ± 11.2 years) had continuous musical training during childhood and adolescence (duration ≥10 years) and six subjects (mean age 42.2 ± 20.1 years) did not. Informed consent and Institutional Review Board approval were obtained for all subjects. Exclusion criteria were: history of hearing or vision problems, history of seizures, metal implants, head trauma with loss of consciousness, or pregnancy.

Subjects were imaged using a Bruker Biospec 30/60 Medspec 3 Tesla MRI scanner equipped with a head gradient insert capable of delivering ±45 mT/m. A 24-slice single-shot spin-echo diffusion echo-planar imaging (EPI)

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sequence was used with the following parameters: matrix = 64 × 128, field of view (FOV) = 19.2 × 25.6 cm, slice thickness = 5 mm, echo time (TE) = 87 ms, repetition time (TR) = 6 s, bandwidth = 125 kHz, big delta (Δ) = 40 ms, little delta (δ) = 18 ms, gradient strength = 30 mT/m, for a b value of 710 s/mm^2. A total of 25 diffusion gradient directions were employed, determined using an electrostatic repulsive model [9], and three scans were acquired without diffusion weighting. Prior to the start of the imaging sequence, two scans were acquired to allow for T1 relaxation. A fluid-attenuated inversion recovery (FLAIR) EPI scan was also acquired with the same imaging parameters as the diffusion tensor sequence for use in correcting for eddy current distortions, and a T1-weighted whole-brain anatomical scan was acquired for anatomical coregistration.

Post-processing was performed using routines written in IDL (Interactive Data Language, Research Systems Inc., Boulder, CO). Eddy current distortion was corrected for via an iterative least-squares algorithm with the FLAIR images used as the reference, rather than the $b = 0$ images in order to prevent excessive stretching due to the differences in signal intensity in the cerebrospinal fluid (CSF) [2]. Geometric distortion due to magnetic field inhomogeneity was corrected for via the multiecho reference method [15]. In order to increase signal to noise, the diffusion images were filtered using a Gaussian filter of width 3 mm. The FA was then computed and transformed into stereotaxic coordinates [19].

Using a k-means clustering algorithm, the white matter and subcortical structures were segmented out from the cortical gray matter and CSF in the averaged whole-brain anatomical image, and subsequent post-processing was only carried out on pixels determined to be within the mask, in order to avoid partial volume effects [10]. On a pixel-by-pixel basis, the effect of musical training on FA values was evaluated using a non-parametric partial correlation analysis, with age and gender being used as covariates. By doing this, we are able to separate our effect of interest (musical training) from the possibly confounding effects of age or gender. In order to correct for multiple comparisons across voxels and increase specificity, the clustering method [20] was used with a cluster size of 15. Regions of at least 15 contiguous voxels with $P < 0.05$ were color-coded and overlaid on the averaged whole-brain anatomical dataset. Monte Carlo simulations performed for the approximately 15,000 voxels in the white matter revealed that the use of a cluster size of 15 resulted in one false positive voxel on average. Regions were identified using the Talairach-atlas [19], and average FA values were then computed for the significantly correlated pixels within the internal capsule and the genu of the corpus callosum.

Greater FA was found in the subjects with musical training in central aspects of the cerebellum (seemingly involving the deep cerebellar nuclei), left and right inferior longitudinal fasciculi, in the left inferior part of the genu of the corpus callosum, and the left and right caudate and

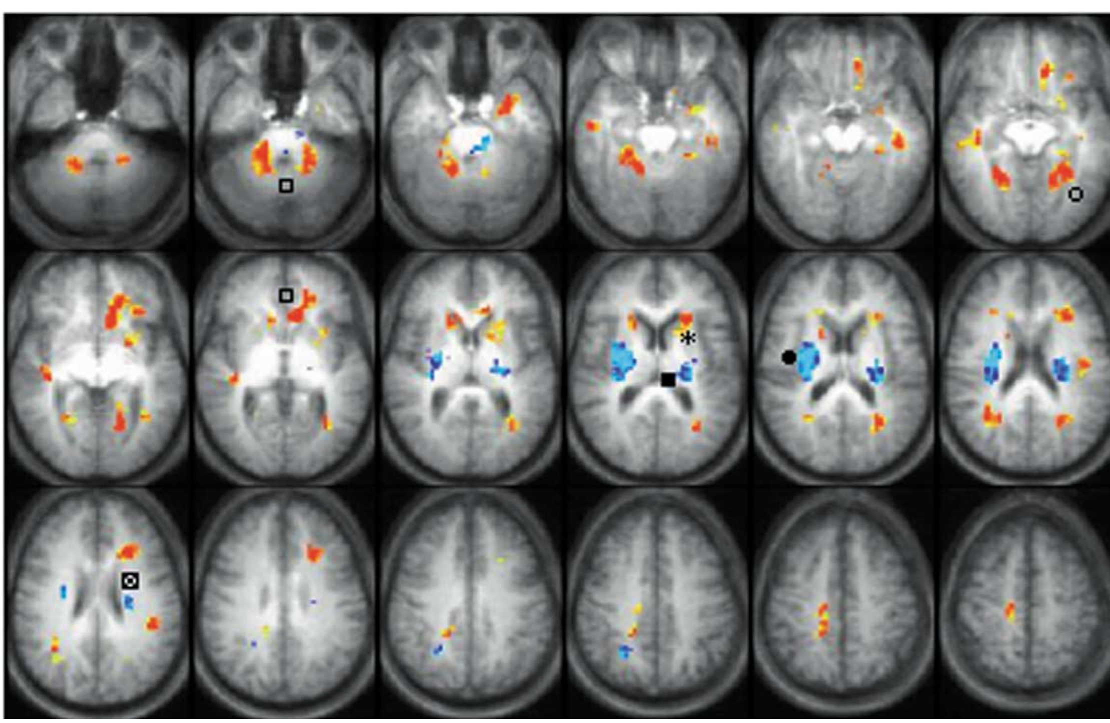

Fig. 1. Areas where FA is significantly greater (red: cerebellum [□], left and right inferior longitudinal fasciculi [○], corpus callosum [◘], and the left and right caudate and putamen [*]) or smaller (blue: thalamus [■], right external capsule/claustrum [●], left and right internal capsule and corona radiata [◙]) in subjects with musical training since early childhood versus controls. Colored pixels have $P < 0.05$ with a cluster size of 15. Differences are overlaid on the averaged whole-brain anatomical dataset (radiological orientation).

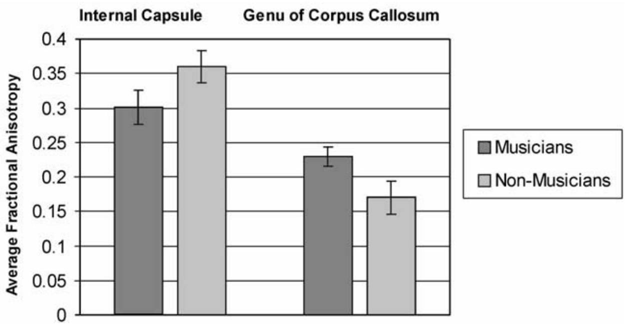

Fig. 2. Comparison of average FA values in the internal capsule and the genu of the corpus callosum between musicians and non-musicians for the correlated pixels shown in Fig. 1. Error bars: ±1 standard deviation; differences in means are significant (Mann–Whitney *U*-test) with $P = 0.005$ (internal capsule); $P = 0.003$ (genu of corpus callosum).

putamen (Fig. 1). Smaller FA was found in the thalamus, the right external capsule/claustrum, and the internal capsule and corona radiata bilaterally. The average FA values computed within the internal capsule (Fig. 2) were significantly smaller ($P = 0.005$, Mann–Whitney *U*-test) in musicians, while the average FA values found within the genu of the corpus callosum were significantly greater ($P = 0.003$, Mann–Whitney *U*-test).

An increase in FA with age during normal development was recently found in the corona radiata and the internal capsule [16], which was attributed to an ongoing maturation and refinement of fine-motor control, especially finger movements during normal development [11]. In contrast to this, FA decreases in the corona radiata have been reported in patients suffering from contralateral hemiparesis or ipsilateral cortical lesions [7]. We think that the seeming contradiction between these results and our findings of decreased FA in musicians compared to non-musicians is explained by the special neural representation of motor control for well-learned, automated movements. Playing a musical instrument involves the repeated and rapid use of multiple defined sequences of fine (finger) movements. These movements must be highly automated in order to be carried out in the accurate and timely fashion necessary to play an instrument, without placing a heavy demand on working memory [4]. Earlier studies investigated this difference in neural representation of novel and learned motor tasks and found that the cerebellum and the striatum are necessary both for the learning of repetitive, complex finger movements and the long-term retention of these 'internal movement models' [4,17]. Since the musicians examined all had continuous musical training for several years, a significant amount of their motor performance has been devoted to the same series of fine motor sequences for a long period of time. Thus, we hypothesize that the heavily repeated use of their 'automated movement'-circuits (namely the striatum and the cerebellum [4,17]) leads to a change in white matter anatomy. This is similar to the phenomenon seen in normal development, i.e. an increase in anisotropy, possibly reflecting an increase in organization at the cellular level [16]. At the same time, the white matter tracts from the primary motor areas (Brodmann's areas 4 and 6) reflect the lesser involvement of these areas relative to normal controls by having a lower degree of anisotropy. This finding seems to be in contrast to the earlier observations of string players showing a greater cortical representation of their left hand [5]. However, a larger area of representation does not necessarily indicate a stronger use of this area: a recent fMRI study showed a significantly weaker hemodynamic response in primary motor areas in professional pianists performing a motor task [8]. Thus, the differences we see in the cerebellum and striatum and in the corticospinal tract (corona radiata and internal capsule) seem to reflect the presence or absence, respectively, of a large repertoire of automated motions, a large degree of use of automated motions, or probably both. Thereby, our findings of differences in white matter structure hint at underlying differences in the extent of usage and/or functional efficiency of primary motor areas.

The finding of an increased FA in musicians in the genu of the corpus callosum is intriguing as morphometric studies between musicians and non-musicians showed a difference in volume of this structure, with the anterior part being bigger in musicians [13]. Functional studies implicated frontal cortical areas on both sides in the recognition and recollection of familiar musical sounds [6] and reported bilateral changes in EEG patterns in frontal and temporal areas on hearing a Mozart sonata [12]. These brain areas therefore seem to serve cognitive processes of musical understanding, and their increased use could lead to an increase in the fibers connecting them.

We have found significant changes in FA values between adult subjects with musical training since childhood and non-musicians. Musicians displayed significantly less FA in the corona radiata and the internal capsule, which we hypothesize to be due to the effects of intensive motor training. Musicians displayed significantly greater FA in the genu of the corpus callosum, which we hypothesize is the result of the cognitive processes involved in music study. We conclude that intensive musical training leads to distinct changes in white matter architecture.

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