Extensive Piano Practicing Has Regionally Specific Effects on White Matter Development

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Extensive piano practicing has regionally specific effects on white matter development

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Using diffusion tensor imaging, we investigated effects of piano practicing in childhood, adolescence and adulthood on white matter, and found positive correlations between practicing and fiber tract organization in different regions for each age period. For childhood, practicing correlations were extensive and included the pyramidal tract, which was more structured in pianists than in non-musicians. Long-term training within critical developmental periods may thus induce regionally specific plasticity in myelinating tracts.

Musicians are a useful group for the study of neural correlates of extensive long-term training[1]. These correlates include structural adaptations in gray matter regions extensive enough to be seen on a macroanatomical level with the use of morphometric techniques[2]. However, white matter in musicians has not been studied as extensively. In humans, the maturation of central fiber tracts continues at least until the age of 30 years, with regional differences in onset time and rate of myelination[3] that have been related to the development of corresponding functions: maturation of frontal and left temporoparietal fiber tracts coincides with the development of working memory capacity and reading ability, respectively[4]. Similarly, the maturation of corticospinal fibers parallels the development of fine finger movements[5]. In the present study, we tested if a fiber tract was susceptible to training-induced plasticity during the period when it was still under maturation. This hypothesis was inspired both by the aforementioned correlations between structural and functional development and by the fact that myelination in the CNS can be stimulated by electrical activity in premyelinated axons[6]. We investigated white matter structure in eight male, right-handed professional concert pianists with a mean age of 32.6 ± 5.7 (s.d.) years, using the magnetic resonance technique diffusion tensor imaging (DTI)[7]. A group of eight male, age-matched non-musicians served as controls. Fractional anisotropy (FA)[7] in each voxel was used as a measure of the degree of water diffusion anisotropy. FA can be used for inferences about the microstructural properties of white matter, as diffusion is faster along axons than in the perpendicular direction (see **Supplementary Methods** online).

We regressed FA on the estimated total number of hours practiced by each pianist during childhood (from the start of practicing until 11 years), adolescence (12–16 years) and adulthood (17 years until time of the magnetic resonance scan). These values were calculated from biographical data collected from all participants on the self-estimated number of hours of practicing from the commencement of piano training until the present. The test-retest reliability of the practicing data was assessed one year later. Significant differences in FA between the pianists and the control group were evaluated with a two-sample *t*-test. The participating pianists started playing at a mean age of 5.8 ± 1.4 years. The mean total number of hours practiced in childhood, adolescence and adulthood for all participants were 1,618 ± 662 h; 3,195 ± 1,515 h and 22,971 ± 9,413 h, respectively. For all three age periods, the test-retest reliability was high. The reliabilities of the measures of childhood, adolescent and adult practicing were $r = 0.81$ ($P = 0.015$), $r = 0.86$ ($P = 0.007$) and $r = 0.95$ ($P = 0.0004$), respectively. Childhood practicing time correlated with practicing time in adolescence ($r = 0.78$, $P = 0.02$; Pearson product-moment correlation). This implies that in the case where a significant regression was found between FA and practicing in both childhood and adolescence in the same brain region, we could not tell whether this reflected practicing in both or in only one of these age periods. Adult practicing time did not correlate significantly with practicing time in childhood ($P = 0.19$) or in adolescence ($P = 0.10$).

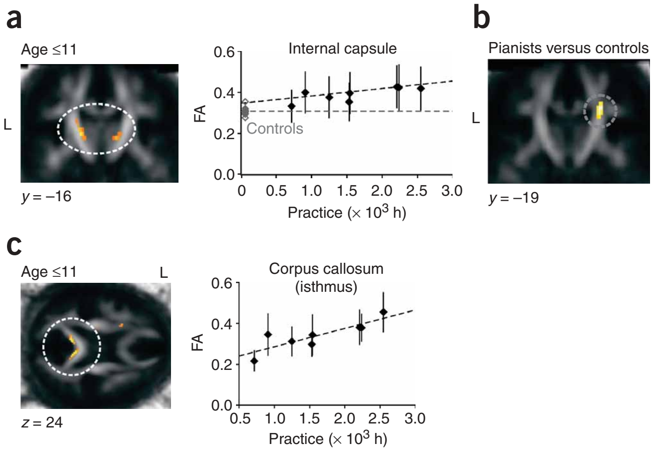

Figure 1 Childhood practicing and white matter structure. (**a**) Clusters in the internal capsule with significant FA correlations, overlaid on the mean FA image from all participants. In the graph at right, each point shows the mean FA value for all voxels in the cluster in one individual. Vertical lines represent s.d. within that participant. Dashed lines are regression lines. (**b**) Cluster of voxels in the right internal capsule with significantly higher FA values in the pianists than in the control group. The mean FA values for each control participant in this cluster are illustrated with gray points in the graph in **a**, and the gray dashed line represents the total mean FA value of the whole control group. (**c**) Same as **a**, for the isthmus of the corpus callosum.

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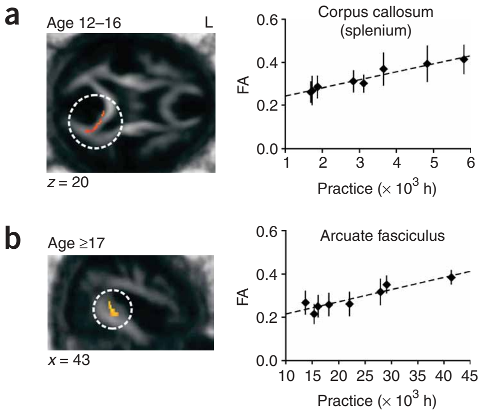

Figure 2 Correlations between adolescent and adult practicing and white matter structure. Cluster images and graphs as in **Figure 1** for (**a**) the splenium of the corpus callosum and (**b**) the right arcuate fasciculus.

A significant correlation between practicing time and FA was found for all age periods, but in different sets of brain regions (**Figs. 1** and **2**, **Table 1**). No correlations were found between FA and the age of the participant. All clusters were located within the white matter in all individual subjects (**Supplementary Figs. 1** and **2**), and no potentially confounding correlations between white matter density and practicing were found in any regions (**Supplementary Methods**).

Childhood practicing correlated with FA in the bilateral posterior limbs of the internal capsule (**Fig. 1a**). The right posterior internal capsule was the only region where significantly higher FA values ($P < 0.000$, $t = 4.34$) were found in the pianist group than in the non-musician group (**Fig. 1a,b**). This cluster had a volume of 1,322 mm^3 with the peak coordinate in 27, –20, –36 (*x*, *y*, *z*) and partly overlapped with the cluster in the same region found in the regression analysis. In addition, childhood practicing correlated with FA in two clusters in the corpus callosum—one in the isthmus extending into the upper splenium (**Fig. 1c**) and the other in the callosal body—and in fiber tracts in the frontal lobe. The posterior limbs of the internal capsule carry the corticospinal tracts[5], which contain descending fibers from the primary sensorimotor and premotor cortices and which are of critical importance for independent finger movements in humans and other primates[8]. The isthmus and adjacent splenium of the corpus callosum contain fibers connecting auditory regions in the superior temporal gyri and the parietotemporal junctions[9]. The body of corpus callosum connects superior frontal regions[9], including the dorsal premotor cortices and the mesial premotor areas, which play key roles for bimanual coordination as well as learning and performance of movement sequences[10,11]. Both the corticospinal tracts and the corpus callosum continue their maturation throughout childhood. Recent work using magnetic resonance imaging has demonstrated age-related changes in corticospinal white matter density continuing at least until an age of 17 years[5]. The maturation of these tracts thus continues well into the period when our participants started practicing the piano.

Practicing during adolescence correlated with FA in the splenium and body of the corpus callosum. The splenium cluster extended into the white matter of the occipital lobe (**Fig. 2a**). As FA in the body and upper splenium of corpus callosum correlated also with childhood practicing, we cannot discuss the relative importance of these two age periods for training-related plasticity in these subregions. The splenium contains interhemispheric fibers from superior temporal and occipital cortical areas[9], which include auditory and visual processing regions, respectively. The cross-sectional area of the corpus callosum grows at least until early adulthood[12]. These age-related changes are mainly due to growth in the posterior and middle regions[13], which is also where FA correlated with practicing in the present study, and could reflect both myelination, which continues at least until age ten[3], and increases in the diameter of callosal axons, as indicated by a decrease in the signal intensity in anatomical magnetic resonance images of the corpus callosum with age[12].

Adult practicing correlated with FA in the left anterior limb of the internal capsule and in a fiber bundle in the right temporoparietal junction (**Fig. 2b**), most likely part of the arcuate fasciculus, which

Table 1 Brain regions with significant correlations between FA values and mean hours of practicing in an age period

Cluster	Side	Corrected *P*-value	Cluster size (mm^3)	r^2	Slope (FA/h × 10^{-4})	Peak coordinate (*x*,*y*,*z*)	Mean FA, pianists (± s.d.)	Mean FA, non-musicians (± s.d.)
Age ≤11								
Corpus callosum (isthmus/splenium)	L	0.02	350	0.88	1.0	–9, –49, 24	0.34 ± 0.10	0.33 ± 0.091
	R	<0.001	648	0.87	0.9	11, –49, 24	0.34 ± 0.11	0.30 ± 0.071
Corpus callosum (body)	R	0.02	350	0.76	0.7	18, –7, 36	0.26 ± 0.063	0.31 ± 0.067
Capsula int., posterior limb	L	<0.001	635	0.83	0.8	–18, –16, 12	0.42 ± 0.10	0.44 ± 0.096
	R	0.025	337	0.84	0.4	14, –13, 8	0.31 ± 0.055	0.33 ± 0.087
Superior frontal	L	0.004	441	0.84	0.6	–25, –2, 36	0.30 ± 0.051	0.32 ± 0.053
	R	0.012	376	0.90	0.6	18, 34, 40	0.27 ± 0.062	0.30 ± 0.051
Inferior frontal	L	0.043	311	0.78	0.6	–18, 31, 0	0.32 ± 0.062	0.30 ± 0.065
Age 12–16								
Corpus callosum (splenium)	R	<0.001	1,257	0.90	0.5	31, –67, 24	0.33 ± 0.083	0.31 ± 0.081
Corpus callosum (body)	R	<0.001	1,024	0.89	0.2	13, –7, 32	0.27 ± 0.059	0.30 ± 0.062
Superior frontal	L	<0.001	648	0.92	0.3	–22, 16, 36	0.27 ± 0.054	0.31 ± 0.064
Age ≥17								
Capsula int., anterior limb	L	0.004	415	0.84	0.08	–16, 7, 12	0.37 ± 0.078	0.40 ± 0.066
Arcuate fasciculus	R	0.004	415	0.90	0.07	47, –29, 0	0.29 ± 0.073	0.28 ± 0.067

The *x*, *y* and *z* coordinates of the peak voxel of each cluster in Talaraich space are given in millimeters.

connects temporal and frontal regions. The most extended myelination cycle is found in corticocortical fibers. The long association fiber systems of the forebrain, which correlated with adult practicing, continue their maturation at least into the third decade of adult life[3].

In summary, these results suggest that training can induce white matter plasticity if it occurs in a period when the involved fiber tracts are still under maturation. We propose that increased myelination, caused by neural activity in fiber tracts during training, is one mechanism underlying the observed FA increases. In the mouse, induction of myelination by neural activity has been demonstrated both *in vivo* and *in vitro*[6], and myelination of the optic nerve is decelerated by rearing in darkness[14]. A key finding here is that the largest number of brain regions correlated with childhood practicing, although the total number of hours practiced in childhood was considerably lower than in later life. In addition, the slope of the regression (that is, change in FA per practice hour) was steeper for early practicing than for adult practicing (**Table 1**). This illustrates both the importance of early practicing for white matter plasticity and the limited malleability of the system in adulthood. The one region where a group difference between pianists and non-musicians was found was the posterior limb of the internal capsule, which also correlated only with childhood practicing. For the corpus callosum and fiber bundles connecting cortical association areas, no group difference was found, although a large proportion of the variance within the musician group was explained by practicing. This may reflect that these regions are involved also in a multitude of non-musical tasks that were practiced by the non-musicians. Professional pianists on average both start their training at an earlier age and practice much more intensively during the first years of training than do amateur players[15]. Our findings suggest one plausible explanation for this: training-induced white matter adaptations are likely to be important for the high-level performance of the mature pianist, and the overall susceptibility to such plasticity is high in childhood, because at that time, a large number of fiber systems used in piano performance have still not completed their maturation. It appears likely that extensive training before the age when involved white matter fiber tracts have fully matured, could be an important factor behind the development of high-level abilities in other domains as well.

Note: Supplementary information is available on the Nature Neuroscience website.

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COMPETING INTERESTS STATEMENT

The authors declare that they have no competing financial interests.

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