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Evidence of cortical thickness increases in bilateral auditory brain structures following piano learning in older adults

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Morphological differences in the auditory brain of musicians compared to nonmusicians are often associated with life-long musical activity. Cross-sectional studies, however, do not allow for any causal inferences, and most experimental studies testing music-driven adaptations investigated children. Although the importance of the age at which musical training begins is widely recognized to impact neuroplasticity, there have been few longitudinal studies examining music-related changes in the brains of older adults. Using magnetic resonance imaging, we measured cortical thickness (CT) of 12 auditory-related regions of interest before and after 6 months of musical instruction in 134 healthy, right-handed, normal-hearing, musically-naive older adults (64–76 years old). Prior to the study, all participants were randomly assigned to either piano training or to a musical culture/music listening group. In five regions—left Heschl's gyrus, left planum polare, bilateral superior temporal sulcus, and right Heschl's sulcus—we found an increase in CT in the piano training group compared with the musical culture group. Furthermore, CT of the right Heschl's gyrus could be identified as a morphological substrate supporting speech in noise perception. The results support the conclusion that playing an instrument is an effective stimulator for cortical plasticity, even in older adults.

Keywords: cortical thickness; music-induced neuroplasticity; elderly; randomized controlled trial; auditory cortex; magnetic resonance imaging

Background

Making music places high demands on the auditory system,[1,2] involving the extraction of auditory features (e.g., pitch, timbre, and location), analyzing melodies, temporal regularities, and processing musical syntax and harmony.[3,4] These neurocognitive processes may induce physiological adaptations that can be examined at multiple levels of the auditory pathway—from peripheral structures, such as the inner ear (e.g., see Ref. 5 for music-related sharpening of cochlear tuning), to central structures, including the primary auditory cortex and higher order auditory regions. In the neurosciences of music, auditory-related brain areas of trained musicians are of particular interest, as it is assumed that their musical experiences are reflected in neuroanatomical structures. The present study focuses on structural changes of selected regions

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of interest (ROI) in the temporal cortex, which are involved in processing auditory stimuli.

There is extensive literature revealing functional and morphological differences in the auditory brain of musicians compared to nonmusicians (for comprehensive reviews, see Refs. 6–8). Using whole brain voxel-based morphometry (VBM) analysis, Gaser and Schlaug[9] compared three levels of musical expertise. They revealed a positive correlation of gray matter (GM) density of both transverse temporal gyri (TTG; also called Heschl's gyri) with musician status, with GM density highest in professional musicians, intermediate in amateurs, and lowest in nonmusicians. Similar findings have been reported,[10,11] showing a gradual increase in GM volumes of TTG from nonmusicians, to amateurs, to professional musicians. This was particularly evident in the volume of the anteromedial portion, which was 130% greater in professional musicians than in nonmusicians.[10] Of particular note is that TTG volume correlated positively with musical aptitude, indicating that differences probably resulted from musical training.[10,11] In comparison to nonmusicians, musicians also showed higher GM concentrations in auditory-related regions adjacent to the TTG, such as the planum temporale (PTe) and planum polare (PPo), as well as the right superior temporal area[12] and left Broca's area.[13] However, more complex patterns of increased and decreased volumes have also been reported; for example, professional pianists showed greater GM volume in the left superior temporal gyrus (STG) but reduced volume in the right STG, compared with nonmusicians.[14]

An alternative to volumetric assessments (e.g., VBM) is the measurement of cortical thickness (CT). Both anatomical traits have been linked to similar neurophysiological mechanisms (e.g., dendritic and axonal arborization, synaptogenesis, neuronal size, and neuropil volume; see Ref. 15), but are based on different calculations: while CT is characterized as the distance between pial surface and the interface of gray and white matter, GM volume is the product of CT and cortical surface area.[16] A variety of studies have shown the adaptability of CT to interventions, such as dancing,[17] balance training,[18] and video game practice.[19] Larger CT following training is traditionally associated with greater benefits in cognitive or sensorimotor abilities;[18,20,21] but potential advantages of smaller CT are also sometimes discussed as proxies for efficiency and automated functioning.[11,12,16,22]

One important study which investigated differences in auditory CT in musicians and nonmusicians was performed by Bermudez *et al.*[12] The authors found greater bilateral CT in musicians, though more in the right superior temporal surfaces encompassing PTe and primary auditory cortex.[12] Similar results were found in musically trained children, who showed larger CT in the right posterior STG and left TTG in comparison to their nonmusical controls.[23]

A major limitation of these cross-sectional studies is that they cannot answer the question of causality; for example, whether musical training or other factors, such as genetic predispositions, are responsible for the neuroanatomical differences between musicians and nonmusicians. To resolve this issue and to corroborate the potency of musical activities for inducing brain plasticity, longitudinal studies are needed.

The first longitudinal study was performed by Hyde *et al.*[24] using deformation-based morphometry analysis. They found that 15 months of instrumental training in children resulted in greater relative voxel size in the right lateral TTG in comparison to the control group. Furthermore, these changes were predicted by improvements of melodic and rhythmic discrimination. In contrast to these clear effects, two later longitudinal studies could not replicate general differences in CT and volume changes of TTG or other auditory-related regions between music and control group(s), but merely trends. Habibi *et al.*[25] found a trend toward a larger reduction in CT and volume of the left versus right posterior STG in 6- to 7-year-old children following 2 years of music training versus controls. The authors interpret this finding as a likely consequence of experience-dependent CT increase due to the strong engagement of the right posterior STG in musical training. In accordance with those results, a trend toward less cortical thinning in the right posterior STG following 4 years of musical instruction has been reported.[23]

Music-driven adaptations can also be measured at the behavioral level. There is broad consensus that musicians have many superior auditory abilities compared to nonmusicians. For example, musicians have a more fine-grained spectrotemporal resolution,[26–28] lower syllable discrimination thresholds,[29] and enhanced auditory attention.[30] In a previous study, we reported improved speech in noise (SIN) perception in older adults after 6 months of playing piano.[31] In addition to corroborating earlier results,[28,32] we also found that the effect occurred particularly in the case of left ear processing, which may indicate music-induced adaptations in more right-lateralized auditory regions that are particularly involved in processing spectral information.[33]

The present analysis, based on a subsample of Worschech *et al.*,[31] has several aims. First, to discover if we can observe music-driven plasticity in older adult brains. Previous studies have shown the relevance of both age[34,35] and the age of onset of musical training[14,36,37] for inducing structural and functional neural changes. They suggest that earlier musical training, especially during the sensitive period(s) before the age of 12, may result in stronger and longer-lasting effects within the auditory system. However, this theory is mainly based on cross-sectional studies or longitudinal studies of children. Investigations of music-related effects in older adults brain are scarce. Second, to investigate the relationships between making music and morphological changes within auditory-related brain regions. We hypothesize larger CT increases in auditory-related areas following piano training in comparison to a musical culture/music listening group. Third, to explore potential relationships between CT and monaural SIN performance. According to earlier results,[31] we hypothesize the right primary auditory cortex to be particularly associated with speech perception.

Methods

Participants and intervention

The present study is part of a comprehensive investigation, including 156 healthy older adults (64-76 years old) from Hanover (Germany) and Geneva (Switzerland). All individuals were right-handed[38] and demonstrated acceptable levels of global cognitive functioning as assessed by the Cognitive Telephone Screening Instrument (COGTEL[39,40]). No participant was dependent on a hearing aid and reported any neurological, psychological, or severe physical health impairments. Prior to the study, all participants had less than 6 months of regular musical practice during their lives. They were randomly allocated to either piano playing (PP) or music listening/musical culture groups (MC) so that both groups were matched in age, sex, education, and COGTEL. The study protocol was published previously[41] and registered on ClinicalTrials.gov (identifier NCT03674931).

Table 1. Demographic information of the sample

	MC	PP
n	67	67
From Geneva (%)	25 (37.31)	28 (41.79)
Years of age (SD)	69.62 (3.90)	69.54 (3.13)
Males (%)	28 (41.79)	28 (41.79)
COGTEL (SD)	30.98 (7.39)	32.16 (7.32)
Income (SD)	2.79 (0.96)	2.88 (0.98)
Education (SD)	3.99 (1.32)	3.87 (1.36)

Income and education levels are defined from 1 to 5 (<25, 25–75, 75–125, 125–175, >175% of national average) and 1–6 (elementary school, middle school, high school, bachelor, masters, PhD), respectively, with higher scores indicating higher socioeconomic status.

Briefly, PP participants learned to play the piano through weekly lessons delivered in groups of three participants, including the teacher. The aim of MC was to get to know and appreciate different music styles through analytic listening and auditory experiencing. Active music making was not allowed in this course. MC was held in small groups of 4–7 participants. In addition to teaching, both courses also included approximately 30 min of daily homework. A detailed curriculum for both courses can be retrieved elsewhere.[31] Twenty-six post-graduate students studying musical performance and education ($n = 21$), music education ($n = 3$), or music theory ($n = 2$) were recruited from local universities to teach PP lessons and MC classes.

During the intervention phase, 10 people dropped out the study. Magnetic resonance imaging (MRI) could not be performed for another 12 subjects; hence, the final analysis is based on 134 participants, whose demographic information is shown in Table 1.

Structural MRI and CT

Before and after 6 months of their allocated intervention, participants were scanned with 3 Tesla MR-Systems. Images were obtained using Siemens Trio (Siemens TIM Trio, Erlangen, Germany) and Siemens Skyra systems (Siemens MAGNETOM Skyra, Erlangen, Germany) in Geneva and Hanover, respectively. At both sites, scanners were equipped with standard Siemens 32-channel head coils. Based on T1-weighted images (MP2RAGE sequence; voxel size: 1 mm isotropic; 176 slices; field of view: 256 × 240 × 176 mm; repetition/echo time: 5000/2.98 ms; inversion time 1/inversion time 2: 700/2500 ms; flip angle 1/2: 4/5 degrees), CT and total intracranial volume (TIV) were automatically computed with the longitudinal pipeline of the Computational Anatomy Toolbox (CAT12[42]) of the Statistical Parametric Mapping software (SPM12). It follows a projection-based thickness approach, which builds on probability maps of standard tissue segmentation into cerebrospinal fluid, white and GM (see Ref. 42 for a full description of the methods). Finally, averaged CT data of six bilateral ROIs, as defined by the Destrieux atlas,[43] and TIV were exported to *R*[44] for statistical analysis (see below).

Regions of interest

We examined 12 ROIs as defined by Destrieux *et al.*[43] in both hemispheres (Fig. 1): (1) anterior transverse temporal gyrus (aTTG); (2) lateral aspect of superior temporal gyrus (lSTG); (3) PPo; (4) PTe; (5) superior temporal sulcus (STS); and (6) transverse temporal sulcus (TTS).

The superior aspect of the temporal lobe can be divided into three areas: the TTG, PPo, and PTe. The anterior portion of the TTG (aTTG) corresponds in part to the primary auditory cortex[43] and represents a key area for auditory processing (first step of cortical processing). The TTS, also known as Heschl's sulcus, divides the TTG from the PTe, which is regarded as a spectrotemporal processor for auditory stimuli.[45,46] A review of neuroimaging studies[47] suggested that a stronger leftward PTe surface asymmetry is associated with musical proficiency. The PPo is located anteriorly to the TTG. The region is implicated in melody generation[48] and the processing of music[49] and pitch.[50] Previous studies suggested a functional lateralization of auditory cortices, in which the left hemisphere is implicated in tasks requiring a high temporal resolution,[51,52] whereas the right auditory cortex and especially the aTTG are particularly involved in processing spectral information.[52,53]

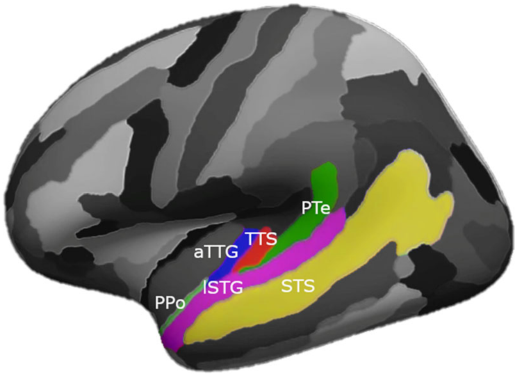

Figure 1. Selection of six bilateral auditory-related ROIs parcellated on the basis of the Destrieux Atlas. aTTG, anterior transverse temporal gyrus; TTS, transverse temporal sulcus; PTe, planum temporale; PPo, planum polare; lSTG, lateral aspect of superior temporal gyrus; STS, superior temporal sulcus.

TTG, TTS, PTe, and PPo all belong to the superior part of the STG and are located inside the Sylvian fissure. The lateral aspect (lSTG) represents the lateral border of these structures and has been associated with phonological processing.[54]

The STS divides the lateral aspect of the temporal lobe into the superior and middle temporal gyri.[43] It is a prominent multisensory integration area. Studies have shown that the STS is implicated in many functions, like theory of mind, social perception, and facial and motion processing, but also audiovisual integration and speech processing (for a review, see Refs. 55 and 56); the latter is particularly associated with activity in bilateral anterior portions.[56]

Speech in noise

To assess SIN, the German[57] and French[58] versions of the International Matrix Test were applied. During this test, the participants had to repeat 20 short and syntactically easy sentences (e.g., "Peter got three large stones") presented via audiometric headphones (Sennheiser HDA 300). The level of the speech-shaped background noise was kept constant at 65 dB, whereas the speech level adapted to the participants' performance. The test aimed for the 50% speech reception threshold (SRT), that is, the relative speech level, at which 50% of words were correctly repeated. To familiarize the participants with the task, 20 sentences were presented binaurally without background noise. This provided an intelligibility score, which was used as a marker for peripheral hearing ability. After familiarization, the test was performed for the left and right ear separately. For detailed information as well as longitudinal results, see Ref. 31.

Statistics

Data analysis was performed within a Bayesian multilevel model framework using the R package *brms*.[59,60] Contrary to frequentist statistics, Bayesian approaches are not based on statistical significance, which may result in dichotomous (significant or not significant) statements. Instead, it returns a *posterior distribution*, which entails all probable effect values. The credible interval (CI) defines the central portion of the posterior distribution, which contains a particular percentage of the effect values. In the present article, 90% CIs are reported, which means that the effect has a 90% probability falling within this range. What CI level to report is more or less an arbitrary choice; however, for the sake of model stability and to dissociate from frequentist approaches, 90% CI levels represent the default in Bayesian analyses.[61] If the CI did not include zero, we assumed the effect very likely to be real. CIs which strongly overlap zero were interpreted as no-effects. In cases where zero was just overlapped, we computed the *probability of direction* (PD) from the R package *bayestestR*.[61] PD computes the probability that a certain parameter (e.g., the effect of time) is strictly positive or negative and thus indexes the effect existence. More information regarding Bayesian statistics and their distinction from frequentist approaches is reviewed in Ref. 62.

In all models, participants' slopes and intercepts were allowed to vary. The variables *time* (pre|post), *sex* (female|male), *site* (Hanover|Geneva), *group* (PP|MC), and *hemisphere* (left|right) were dummy coded (0|1). All outcome variables and predictors except *time, group,* and *hemisphere* were centered and transformed to z-scores with a mean of zero and a standard deviation of one. Thus, the reference level was defined by PP's left hemisphere at baseline. To investigate differences in CT changes between PP and MC, we included *time–group* interactions in the model. Because those interactions refer only to the left hemisphere, we expanded the interactions by a third variable *hemisphere*. These three-way interactions incorporate the right hemisphere into the model and allow a comparison between homotopic brain regions (e.g., left aTTG and right aTTG). To directly probe certain effects (e.g., group differences of regional CT changes within the right hemisphere), we applied the hypothesis function. Additionally, CT was adjusted for the weighted score of the COGTEL, age, intelligibility, and TIV.

All models converged without problems. Rhat-values, which provide information on the convergence of the Markov Chain Monte Carlo algorithm, were below the critical threshold of 1.1. By visual inspection, all chains were well mixed. Posterior predictive checks, applied by using the function *pp_check* with 100 draws (simulations), indicated a good model fit. Detailed model parameters and output are provided in Table S1 (online only).

Furthermore we explored whether left and right SIN perception can predict CT of each ROI. Therefore, we standardized left and right SIN perception scores and added the variable to the multilevel models. To account for differences in left and right hemispheres, we also included a hemisphere–SIN interaction. Since left and right SIN are strongly correlated with intelligibility ($r_{\text{left}} = -0.56$, $r_{\text{right}} = -0.52$) as well as with each other ($r = 0.72$), we excluded intelligibility and calculated the models for left and right SIN separately.

Results

Generally, all models revealed strong variance of intercepts and slopes across participants. Both were negatively correlated, that is, the greater CT at baseline, the lower was the CT increase over the 6 months intervention period.

In none of the models, age and COGTEL were clearly predictive of CT except for PTe, where higher age predicted a slight increase in CT (0.11 [0.00; 0.21]). Intelligibility was found to be meaningful for bilateral aTTG (left: 0.16 [0.05; 0.28]; right: 0.27 [0.15; 0.38]) and left PPo (0.14 [0.02; 0.25]), where better hearing predicted greater CT.

Anterior transverse temporal gyrus

After the 6-month intervention, opposite cortical developments occurred in both groups. While PP showed a credible (PD = 90.3%) CT increase in the left aTTG (0.14 [−0.04; 0.32]), MC showed a CT decrease (−0.17 [−0.35; 0.01]). This is reflected in a meaningful *time–group* interaction (−0.31 [−0.56; −0.06]). Although the direction of the effect was the same for the right aTTG (−0.16 [−0.42; 0.09]), the *time–group* interaction was weaker compared to the left portion, and an advantage of PP over MC was less likely (PD = 85.6%) (Fig. 2A).

Lateral aspect of STG

For the lSTG, effects of *sex* and *hemisphere* manifested. Men seem to have less CT than women in the

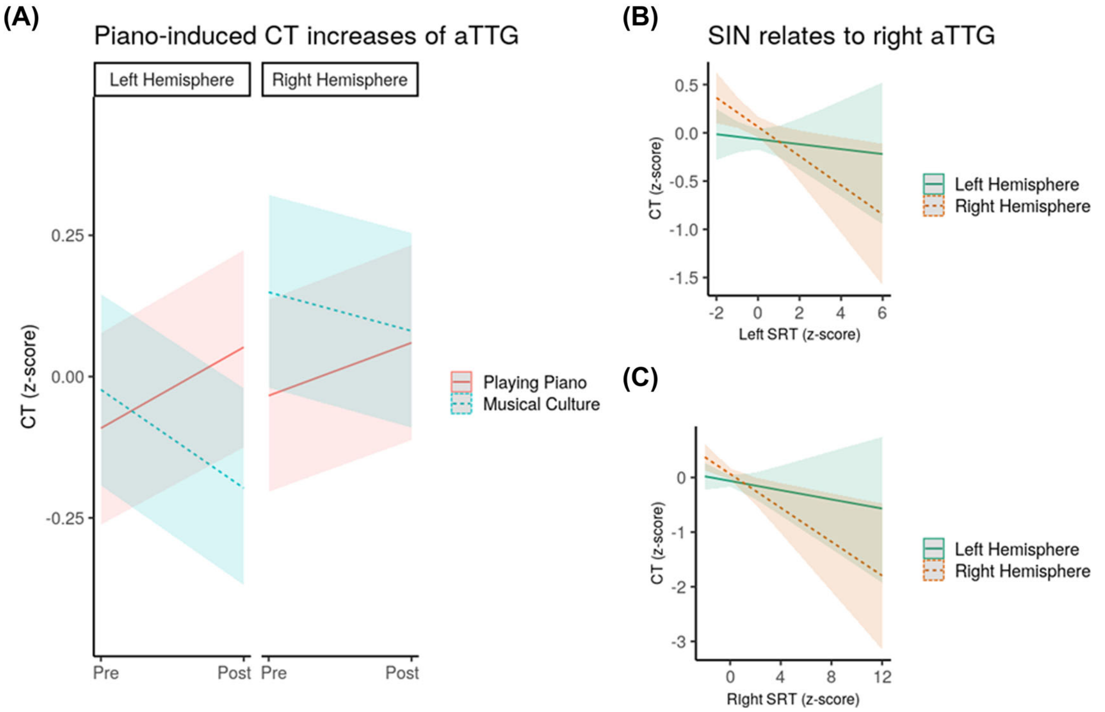

Figure 2. CT of the left aTTG developed differently across groups, with a CT increase in PP (A). SIN performance meaningfully predicted CT of the right aTTG, where lower (i.e., better) SRTs were associated with greater CT (B and C). Predicted median with shaded 90% CI.

lSTG (−0.23 [−0.52; −0.06]), and right lSTG shows increased CT than the contralateral portion (0.25 [0.12; 0.38]). Neither *time* nor *time–group* interactions occurred in the lSTG.

Planum polare and planum temporale

PPo showed effects of *hemisphere* and *site*, indicating less CT in the right hemisphere (−0.26 [−0.41; −0.10]) and greater CT in the Swiss population (0.43 [0.20; 0.65]).

While PP participants showed a CT increase in their left PPo (0.18 [0.00; 0.36]), MC showed the opposite effect (−0.19 [−0.38; −0.01]). The *time–group* interaction was statistically meaningful (−0.38 [−0.36; −0.12]). Neither an effect of *time* nor *time–group* interaction was associated with the right hemisphere. No effects were found in the PTe.

Superior temporal sulcus

STS showed strong left-right asymmetries, with greater CT in the right portion (0.58 [0.46; 0.70]). Furthermore, men showed less CT than women (−0.20 [−0.48 −0.07]).

While in PP the CT in bilateral STS remained constant, MC showed bilateral CT loss (left: −0.19 [−0.35; −0.03]; right: −0.24 [−0.4; −0.09]). *Time–group* interaction for the left STS indicated a likely (PD = 92.7%) reduction in CT compared to PP (−0.20 [−0.42; 0.03]). For the right side, the group differences were even stronger, indicating a statistically meaningful *time–group* interaction (−0.31 [−0.53; −0.08]), with MC showing a CT decrease, whereas PP displayed increased CT.

Transverse temporal sulcus

An effect of site was found for the TTS, with less CT in the Swiss sample (−0.25 [−0.48; −0.02]). In the left TTS, no CT changes were observed across MC and PP. Regarding the right TTS, however, PP exhibited a CT increase (0.18 [0.00; 0.36]), whereas MC showed the opposite effect (−0.21 [−0.39; −0.03]), resulting in a meaningful *time–group* interaction (−0.38 [−0.64; −0.13]).

Speech in noise

After reporting music-related improvements in monaural SIN perception,[31] we investigated whether SIN perception is able to predict CT of the ROI in the present analysis. Left SIN perception predicted CT of the right aTTG (−0.15 [−0.27; −0.03]) (Fig. 2B), bilateral lSTG (−0.12 [−0.24; −0.01]), and left PPo (−0.15 [−0.27; −0.03]). Right SIN perception predicted CT of the right aTTG (−0.16 [−0.27; −0.05]) (Fig. 2C), right PTe (−0.18 [−0.29; −0.07]), and bilateral TTS (left: −0.16 [−0.27; −0.05]; right: −0.17 [−0.28; −0.06]). For all these regions, better SIN perception (i.e., lower SRTs) was associated with greater CT.

Discussion

After 6 months of intervention, we found greater CT increases in 5 out of 12 auditory-related ROIs in PP when compared to MC. These regions comprised the left aTTG, left PPo, bilateral STS, and right TTS. In PP, three regions (left aTTG, left PPo, and right TTS) showed CT increases, and none of the 12 regions showed a statistically meaningful CT loss during piano training. In comparison, MC recorded no CT increases in any region, and five regions (left aTTG, left PPo, bilateral STS, and right TTS) even thinned during the 6-month intervention.

The strongest *time–group* interactions were found in the left PPo and right TTS, areas which are, among others, associated with pitch processing,[20,50] melody generation,[48] and the processing of music.[49] All skills were required in the piano training. Considering the, albeit marginal, piano training–induced effect on the CT increase of the right aTTG and its association with left and right SIN perception, we suggest that music-related SIN improvements benefit from induced fine-grained spectral resolution,[28,63] whose general neurocomputational hub might be located in the right aTTG.[52,53] The right aTTG might thus be an anatomical substrate responsible for the SIN advantages of musicians over nonmusicians[30,63] or in SIN improvements following musical training.[31,64]

Left and right SIN performances were also related to CT in the lSTG, right PTe, and left TTS, where no group differences between PP and MC groups occurred. In total, CTs from eight out of 12 ROIs were associated with monaural SIN performance. These results argue in favor of a strong anatomo-behavioral relationship between CT and SIN at the level of the auditory cortex, which is consistent with functional MRI evaluation of speech processing.[65] This, in addition, is in accordance with an overview of receptive speech processing studies showing an overlap between structural and functional correlates in the same regions.[66]

Hearing loss and communication difficulties represent a common problem among older adults.[67] The World Health Organization ranks hearing loss as the fourth leading cause of disability worldwide and recommends urgent public health action.[68] Because piano training can counteract age-related decline in speech comprehension,[31] musical engagement should be considered as a potential prevention or rehabilitation strategy that can also be expected to have a profound impact on the quality of life of older people.[69]

It should be noted that SIN perception might also be connected to neural substrates that were not evaluated by our auditory-related ROI approach, such as regions involved in inhibitory control or attention.[70,71] Further research is needed to explore music-related SIN effects and their structural correlates at the whole brain level. One limitation of our study is the lack of audiometric measurements (e.g., PTA testing) to exclude participants with mild or moderate hearing loss. However, no participant reported major hearing problems or wearing a hearing aid. In addition, we controlled for peripheral hearing ability by including the intelligibility score in the statistical models.

According to our results, playing the piano does not only prevent age-related brain thinning, but can even cause a CT increase in certain brain areas in older adults. We have demonstrated that playing an instrument is an effective stimulator for cortical plasticity, which lasts into aging—more than 50 years after the sensitive period(s) of musical training.[37] Furthermore, our work complements previous cross-sectional results and suggests that the differences in auditory brain regions of musicians compared to nonmusicians are at least partly due to musical training, and not only caused by preexisting factors.

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Author contributions

F.W. wrote the initial draft of this manuscript. D.M., F.W., and K.J. acquired the data. C.A.H.M. preprocessed the MRI data. F.W. performed the statistical analysis. C.E.J. and E.A. wrote the grant proposal submitted to the DFG (Deutsche Forschungsgemeinschaft) and SNSF (Swiss National Science Foundation). M.K. and T.H.C.K. gave detailed input to the grant application. All authors critically reviewed, revised the article, and approved the submitted manuscript.

Supporting information

Additional supporting information may be found in the online version of this article.

Table S1. Detailed model parameters and output.

Competing interests

The authors declare no competing interests.

Peer review

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