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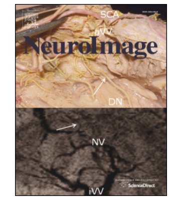

Structural neuroplasticity in expert pianists depends on the age of musical training onset

Lucía Vaquero [a,b,*,1], Karl Hartmann [c,d,1,2], Pablo Ripollés [a,b], Nuria Rojo [a,b], Joanna Sierpowska [a,b], Clément François [a,b], Estela Càmara [a], Floris Tijmen van Vugt [d,3], Bahram Mohammadi [e,f], Amir Samii [f], Thomas F. Münte [e], Antoni Rodríguez-Fornells [a,b,g], Eckart Altenmüller [d,**]

[a] Cognition and Brain Plasticity Unit , Bellvitge Research Biomedical Institute (IDIBELL), Hospital Duran i Reynals, 3rd floor, Gran Via de l'Hospitalet, 199 L'Hospitalet de Llobregat, 08908 Barcelona, Spain
[b] Dept. of Basic Psychology, University of Barcelona, Pg. Vall d'Hebrón, 171, 08035 Barcelona, Spain
[c] Medical School of Hannover (MHH), Carl-Neuberg-Str., 1, 30625 Hannover, Germany
[d] University of Music, Drama and Media, Institute of Music Physiology and Musicians' Medicine, Emmichplatz, 1, 30175 Hannover, Germany
[e] Department of Neurology, University of Lübeck, Ratzeburger Allee, 160, 23538 Lübeck, Germany
[f] CNS-LAB, International Neuroscience Institute (INI), Rudolf-Pichlmayr-Str., 4, 30625 Hannover, Germany
[g] Institució Catalana de Recerca i Estudis Avançats (ICREA), Pg. Lluís Companys, 23, 08010 Barcelona, Spain

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A B S T R A C T

In the last decade, several studies have investigated the neuroplastic changes induced by long-term musical training. Here we investigated structural brain differences in expert pianists compared to non-musician controls, as well as the effect of the age of onset (AoO) of piano playing. Differences with non-musicians and the effect of sensitive periods in musicians have been studied previously, but importantly, this is the first time in which the age of onset of music-training was assessed in a group of musicians playing the same instrument, while controlling for the amount of practice. We recruited a homogeneous group of expert pianists who differed in their AoO but not in their lifetime or present amount of training, and compared them to an age-matched group of non-musicians. A subset of the pianists also completed a scale-playing task in order to control for performance skill level differences. Voxel-based morphometry analysis was used to examine gray-matter differences at the whole-brain level. Pianists showed greater gray matter (GM) volume in bilateral putamen (extending also to hippocampus and amygdala), right thalamus, bilateral lingual gyri and left superior temporal gyrus, but a GM volume shrinkage in the right supramarginal, right superior temporal and right postcentral gyri, when compared to non-musician controls. These results reveal a complex pattern of plastic effects due to sustained musical training: a network involved in reinforcement learning showed increased GM volume, while areas related to sensorimotor control, auditory processing and score-reading presented a reduction in the volume of GM. Behaviorally, early-onset pianists showed higher temporal precision in their piano performance than late-onset pianists, especially in the left hand. Furthermore, early onset of piano playing was associated with smaller GM volume in the right putamen and better piano performance (mainly in the left hand). Our results therefore reveal for the first time in a single large dataset of healthy pianists the link between onset of musical practice, behavioral performance, and putaminal gray matter structure. In summary, skill-related plastic adaptations may include decreases and increases in GM volume, dependent on an optimization of the system caused by an early start of musical training. We believe our findings enrich the plasticity discourse and shed light on the neural basis of expert skill acquisition.

* Correspondence to: L. Vaquero, Universitat de Barcelona, Campus de Bellvitge, Pavelló de Govern. Dept. Neuropsicologia, c/ Feixa Llarga, s/n, 08907, L'Hospitalet de Llobregat, Barcelona, Spain.
** Corresponding author.
E-mail addresses: lucia.vaquero.z@gmail.com (L. Vaquero), karl.hartmann@stud.mh-hannover.de (K. Hartmann), pablo.ripolles.vidal@gmail.com (P. Ripollés), nuriarojofite@gmail.com (N. Rojo), joanna.sierpowska@gmail.com (J. Sierpowska), fclement24@hotmail.com (C. François), ecamara@ub.edu (E. Càmara), floris.vanvugt@mail.mcgill.ca (F.T. van Vugt), mohammadi@ini-hannover.de (B. Mohammadi), a.samii-office@ini-hannover.de (A. Samii), thomas.muente@neuro.uni-luebeck.de (T.F. Münte), arfornells@gmail.com (A. Rodríguez-Fornells), eckart.altenmueller@hmtm-hannover.de (E. Altenmüller).
[1] Equally contributed to this work.
[2] Present address (Hartmann, K.): Neurochirurgisches Forschungslabor, KRH Klinikum Nordstadt, Haltenhoffstrasse 41, 30167 Hannover, Germany.
[3] Present address (van Vugt, Floris): Motor control lab, Psychology Department, McGill University, 1205 Dr Penfield Avenue, H3A 1B1 Montreal, Canada.

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Introduction

Professional musicians constitute an ideal group to study learning-related neuroplasticity (Schlaug et al., 1995; Münte et al., 2002; Gaser and Schlaug, 2003; Bengtsson et al., 2005; Bermudez et al., 2009; Imfeld et al., 2009) due to the intensity and scope of their training. Musical practice involves the development of fine motor skills, bimanual coordination, audio–motor integration, as well as cognitive processes, such as memory, attention and executive functions, all under the high motivational drive of the intrinsic emotional power of music (Schmithorst and Wilke, 2002; Zatorre et al., 2007; for a review see Jäncke, 2009 and Koelsch, 2010). Extensive musical practice during childhood and adolescence might have a strong effect on the development of brain structures. Importantly, this might be a bidirectional process: while music training promotes neuroplastic changes that enhance several underlying brain functions, this enhancement in brain structure and function might also improve music performance and learning (Pascual-Leone, 2001). Due to a high demand on bimanual dexterity, keyboard players have been a preferred group to study structural and functional brain changes (Amunts et al., 1997; Watson, 2006; Bangert et al., 2006). In a pioneering study, Schlaug et al. (1995) showed that professional musicians (pianists and string-players) had a larger middle section of the corpus callosum compared to a non-musician control group. Furthermore, those musicians who began their training before the age of 7 showed a larger anterior part of the corpus callosum compared to those with a late training onset. In a diffusion tensor imaging (DTI) study with pianists, Bengtsson et al. (2005) found that several white matter tracts correlated with the estimated amount of musical practice during childhood (e.g. posterior limb of internal capsule, the isthmus and the body of corpus callosum, and some fiber tracts in the frontal lobe), although the total number of practicing hours was lower in this period than the estimated hours in adolescence and adulthood. These results support the idea that the central nervous system exhibits greater plastic capacities during early stages of development and maturation periods, contrasting with its limited malleability during adulthood.

Previous studies have demonstrated the importance of the age of onset (AoO) of musical training in influencing brain plasticity. For instance, Amunts et al. (1997) affirmed that early musical training could lead to pronounced anatomical changes in the hand motor area. Similarly, a seminal magnetoencephalography (MEG) study (Pantev et al., 1998) showed that the dipole strength associated with piano tones was greater in the auditory network of those musicians who had begun practicing before the age of 9 years thus favoring the idea that the age of inception of musical training is important in determining the degree of cortical adaptation (Elbert et al., 1995; Amunts et al., 1997). The relevance of the AoO in relation to the performance level is generally confounded because early starters usually accumulate a larger amount of practice time. The relationship between sensitive periods and the level of expertise, and between these and the degree of anatomical predispositions or adaptations, is unclear at this point. Recent studies referring to one group of right handed early-onset and late-onset musicians show gray and white matter differences and enhanced timing skills in a finger tapping auditory–motor task in early-onset musicians. Via deformation-based morphometry, cortical gray matter differences in the right ventral premotor cortex were observed (Bailey et al., 2014), and using a novel multi-atlas automatic segmentation pipeline, smaller cerebellar gray matter volumes in the right lobule VI were shown (Baer et al., 2015). Using diffusion tensor imaging, Steele et al. (2013) found a higher fractional anisotropy in the isthmus of the corpus callosum. All of these morphological differences between the early- and late-onset groups correlated with their timing skills in an auditory–motor synchronization task using the right index finger: the earlier the start of music training, the better the performance in the synchronization task. In a recent study with selected highly trained pianists, Granert et al. (2011) measured the skill level of piano playing via the temporal accuracy during a scale-playing task. These authors found that the higher the skill level of piano playing, the smaller the volume of gray matter in the right middle putamen.

Broadening the concept of expertise, Gaser and Schlaug (2003) compared professional keyboard players, amateur keyboard players and non-musicians and reported increased GM volume in primary motor, somatosensory, and premotor areas, among other regions in the musician groups. James et al. (2014) applied a regression analysis over a three-group population modeling expertise in the same way as Gaser and Schlaug (2003), trying to find the areas in which professional musicians > amateur musicians > non-musicians (or vice versa) differed, while controlling for training intensity. They found an intricate pattern of increased/decreased GM. In particular, musicians showed GM density increases in areas related to higher-order cognitive processes (such as the fusiform gyrus or the inferior frontal gyrus), whereas GM decreases were found in sensorimotor regions (as perirolandic and striatal areas). These reductions in GM were interpreted as reflecting a higher degree of automaticity of motor skills in more expert musicians (James et al., 2014).

With the present investigation, we aimed to examine brain differences between a homogeneous group of selected musicians and a control group of non-musicians. In order to avoid any confounds, we restricted our analysis to extremely skilled and highly performing, award-winning concert pianists from the Hannover University for Music, Drama and Media. This is the first time that the effects of musical training depending on the AoO are addressed in such a homogeneous cohort of expert pianists, taking into account both AoO and amount of practice. Although previous literature seems to point to an improved neural system in musicians with a higher level of expertise (acquired after long periods of training), the results of studies either focusing on gray (Han et al., 2009) or white-matter differences (Oechslin et al., 2010) as a function of AoO of musical training are not clear cut. Thus, we divided the musician sample in pianists who began to play piano before age 7 (early) and after or at age 7 (late). This cutoff is widely accepted among plasticity researchers as a crucial age for starting musical training (Schlaug et al., 1995; Bengtsson et al., 2005; Steele et al., 2013; Penhune and de Villers-Sidani, 2014; Bailey et al., 2014; Baer et al., 2015; see reviews by Wan and Schlaug, 2010, and Penhune, 2011). Thus, the main goal of our study was to examine the effect of music training and age of onset in the GM structure of expert pianists. Voxel-based morphometry (Ashburner and Friston, 2000) was used and based on previous literature, GM differences in areas related with motor, auditory and emotional processing were expected (see Table 1 for a summary of previous studies on neuroplasticity in musicians). Moreover, a scale-playing task was administered to the pianists in order to control for differences in performance skill between the early- and late-onset groups. Playing a scale on the piano is a demanding task, and the subtle timing differences detectable using this task have previously been shown to be a reliable and highly relevant indicator of pianistic expertise (Jabusch et al., 2009; van Vugt et al., 2014).

Materials & methods

Participants

Forty-one expert pianists and seventeen non-musicians participated in the study. All participants (both pianists and non-musicians) reported to be right-handed. Five participants from the pianists group were removed from the final analysis due to strong motion artifacts, thus leading to a final group of 36 musicians split into early (age of onset < 7 years; $n = 21$, 12 females; 15 caucasians, 6 asians) and late starters (age of onset ≥ 7 years; $n = 15$, 7 females; 12 caucasians, 3 asians). AoO of piano playing between early- and late-onset pianists was significantly different ($p < .001$). On the one hand, musicians were either advanced master-class piano students or professional pianists having graduated with piano as a major from the Hannover

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