Neuroplasticity, music, and human brain

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Abstract

Introduction. *Studying the influence of music on the human brain is one of the key topics in neuroscience as it allows extending our understanding of brain neuroplasticity.*
This study aimed *to investigate structural brain organization in professional musicians.*
Materials and methods. *We investigated 27 brains (i.e. 54 hemispheres) of male musicians, female musicians, male non-musicians, and female non-musicians by magnetic resonance imaging. All study participants were aged 20 to 30 years and did not have any mental or neurological disorders. Gray matter volume and cortex thickness in different cortical structures of the right and left hemispheres were measured.*
Results. *We found major changes in the brain structure in professional musicians (both male and female) vs. non-musicians. We found differences in the macroscopic structure of the triangular region in the Broca's motor speech area in musicians' brain. Increases in gray matter volume in the brain of musicians and its individual cortical structures were shown in the superior temporal region, Broca's motor speech area, hippocampus, superior parietal lobule, and other structures. We found increased thickness of cortical structures in musicians vs. non-musicians.*
Conclusions. *Practicing music regularly was shown to change structural brain organization; we found significant increases in gray matter volume and cortex thickness in various cortical structures in the right and left brain hemispheres of musicians vs. non-musicians.*

Keywords*: brain; male; female; music; cortical structures*

Ethics approval. The study was conducted with the informed consent of the patients. The research protocol was approved by the Ethics Committee of the Research Center of Neurology (protocol No. 7-4/22, August 29, 2022).

Source of funding. This study was not supported by any external sources of funding.

Conflict of interest. The authors declare no apparent or potential conflicts of interest related to the publication of this article.

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For citation: Bogolepova I.N., Krotenkova M.V., Konovalov R.N., Agapov P.A., Malofeeva I.G., Bikmeev A.T. Neuroplasticity, music, and human brain. *Annals of Clinical and Experimental Neurology*. 2024;18(1):72–78. (In Russ.)

DOI: https://doi.org/10.54101/ACEN.2024.1.8

Received 20.05.2023 / Accepted 19.10.2023 / Published 25.03.2024

Нейропластичность, музыка и мозг

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Аннотация

Введение. *Изучение влияния музыки на мозг человека является одной из важных проблем нейронауки, т.к. позволяет расширить наше представление о нейропластичности мозга.*
Цель *исследования – изучение особенностей структурной организации мозга профессиональных музыкантов.*
Материалы и методы. *С помощью магнитно-резонансной томографии исследовали 27 мозгов (54 полушария) мужчин-музыкантов, женщин-музыкантов и людей, не имеющих отношения к музыке. Все исследуемые были в возрасте 20–30 лет, без неврологических и психических заболеваний. Измеряли объём серого вещества и толщину коры различных корковых формаций в правом и левом полушариях мозга.*
Результаты. *Установлены принципиальные изменения строения мозга профессиональных музыкантов (мужчин и женщин) в сравнении с мозгом людей, не имеющих отношения к музыке. Отмечены особенности макроскопического строения триангулярной области речедвигательной зоны Брока мозга музыкантов. Установлено увеличение объёма серого вещества мозга музыкантов и его отдельных корковых формаций, в частности, верхней височной извилины, речедвигательной зоны Брока, гиппокампа, верхней теменной дольки и ряда других структур. Показано увеличение толщины коры корковых структур мозга музыкантов в сравнении с мозгом немузыкантов.*

Заключение. *Систематические занятия музыкой изменяют структурную организацию мозга, установлено значительное увеличение объёма серого вещества и толщины коры различных корковых формаций в правом и левом полушариях мозга музыкантов по сравнению с людьми контрольной группы.*

Ключевые слова*: мозг; мужчина; женщина; музыка; корковые формации*

Соблюдение этических стандартов. Исследование проводилось при добровольном информированном согласии пациентов. Протокол исследования одобрен Этическим комитетом Научного центра неврологии (протокол № 7-4/22 от 29.08.2022).

Источник финансирования. Авторы заявляют об отсутствии внешних источников финансирования при проведении исследования.

Конфликт интересов. Авторы декларируют отсутствие явных и потенциальных конфликтов интересов, связанных с публикацией настоящей статьи.

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Для цитирования: Боголепова И.Н., Кротенкова М.В., Коновалов Р.Н., Агапов П.А., Малофеева И.Г., Бикмеев А.Т., Нейропластичность, музыка и мозг. *Анналы клинической и экспериментальной неврологии*. 2024;18(1):72–78.

DOI: https://doi.org/10.54101/ACEN.2024.1.8

Поступила 20.05.2023 / Принята в печать 19.10.2023 / Опубликована 25.03.2024

Introduction

Neuroplasticity or brain plasticity is one of the key topics in neuroscience. The term neuroplasticity refers to the ability of the brain to change its function and structure under the influence of external environment, professional activity, or psychological stress [1–5].

Santiago Ramón y Cajal was one of the first researchers to use the term neural plasticity; however, he used it to describe the neuron as a key and fundamental brain unit. Afterwards, this term was used mainly to describe regeneration of peripheral nervous system [6].

The use of microelectrodes in neurophysiological studies allowed researchers to record electrical signals from neurons and, therefore, to elucidate interactions between individual neurons by drawing structural and functional maps of the brain. In the 1960s, D. Hubel and T. Wiesel studied animals' brain and showed that the brain had greater plasticity in younger animals, especially between Week 3 and Week 8 of the postnatal period. By showing changes in the functioning of cortical brain structures in animals with visual impairment, these authors also demonstrated for the first time that the functional map of the brain can change [7–9].

Further experimental studies showed the ability of structural and functional brain maps to change [10–12].

Studies to evaluate the brain of healthy human subjects and patients by magnetic resonance imaging (MRI) greatly contributed to understanding neuroplasticity. For the first time, changes in people's brain related to their professional activity were shown.

Music is an essential component of human emotional life. Many modern publications clearly demonstrated that music influenced human memory, rhythm, and perception of time. Listening to music, people can calm down and relax, or music can make them move or dance. Practicing music professionally can reshape a person's life [13, 14]; however, there are very few studies, if any, to evaluate musicians' brains.

This study aimed to investigate structural brain organization in professional musicians.

Materials and methods

A total of 27 brains (i.e. 54 hemispheres) of 9 male non-musicians, 9 female non-musicians, 5 male musicians, and 4 female musicians were studied by MRI. All study subjects were aged 20 to 30 years and did not have any mental or neurological disorders. All male and female musicians have been playing the piano since their childhood and had a university degree in music (i.e. piano). Currently they worked as piano teachers, accompanists or gave recitals.

Study subjects provided informed consent to participate in the study. The study protocol was approved by the Ethics Committee of Research Center of Neurology (Protocol 7-4/22, August 29, 2022).

We measured total volume of the gray matter, white matter, several cortical structures, inferior frontal gyrus, opercular region of Broca's motor speech area, parahippocampal gyrus, superior temporal gyrus, temporal pole, and other brain structures, as well as cortex thickness in several brain regions.

The study was performed using an ultra-high-field Siemens MAGNETOM Prisma MRI scanner in T1 MP2RAGE sequence in the sagittal plane with 176 slices, slice thickness of 1 mm, scanning parameters TR = 5000.0 ms, TE = 2.74 ms, TI1 = 700 ms, TI2 = 2500 ms, flip angle$_1$ = 4°, flip angle$_2$ = 5° and matrix size of 256 mm. Brain surface was reconstructed by processing MRI images using CAT12 MRI data processing toolkit, which was created using Matlab package. The Segment module was used according to the standard procedure described in the CAT12 application manual. Gray matter volume and cortex thickness were measured using CAT12 in the ROI Tools module with neuromorphometrics and parc_a2009s_thickness atlases.

Data were processed statistically using Statistica v. 8 and Rver.4.x software packages. Differences between brain parameters of musicians and non-musicians were assessed for significance using non-parametric statistics with Mann – Whitney U-test. Differences were considered significant if the level of statistical significance *p* was less than 0.05. For the ease of data representation in the article, median values (*M*) and interquartile ranges (Q_1–Q_3) were provided.

Results

We found major changes in the brain structure of male musicians *vs.* male non-musicians and female musicians *vs.* female non-musicians. An analysis to compare the macroscopic structure of the Broca's area in the left hemisphere (LH) showed that female musicians had more complex structure of the triangular region in the brain cortex compared with female non-musicians. Additional grooves were seen in the brain of female musicians compared with female non-musicians (especially in the triangular region), as well as merging of the triangular region with the opercular region and the orbital region of the brain due to the presence of interstitial formations, which increased the size of both the triangular and opercular regions (Fig. 1, 2).

In male musicians, relative volume of the gray matter as a percentage of total brain volume was greater than in male non-musicians (p = 0.048): median relative volume of the gray matter as a percentage of total brain volume was 36.00% ± 4.05% in male non-musicians and 40.25% ± 3.68% in male non-musicians. In women, differences were not considered significant (p = 0.44; Fig. 3).

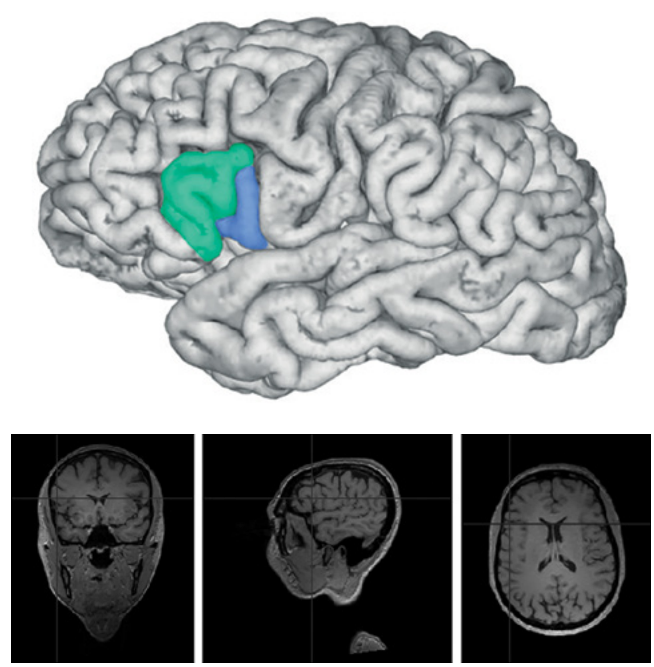

Fig. 1. Structure of Broca's area in the brain of a female musician, LH.
Triangular region is shown in green; opercular region is shown in blue.

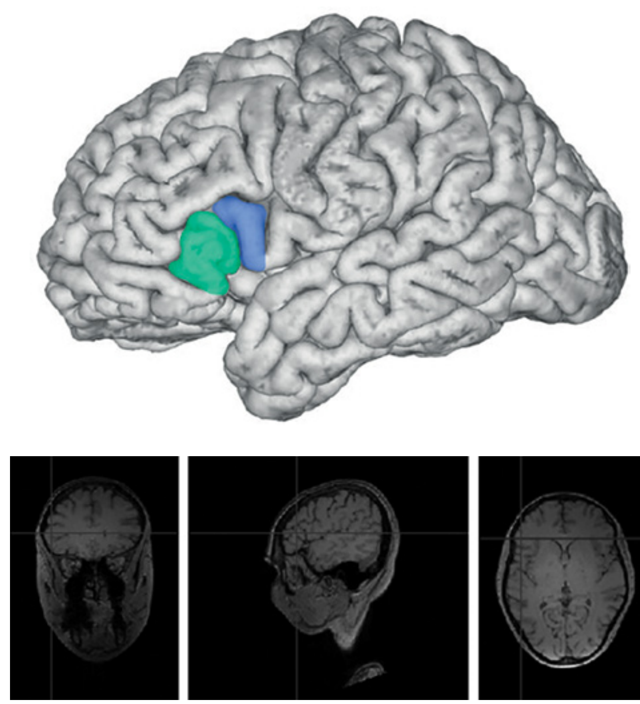

Fig. 2. Structure of Broca's area in the brain of a female non-musician, LH.
Triangular region is shown in green; opercular region is shown in blue.

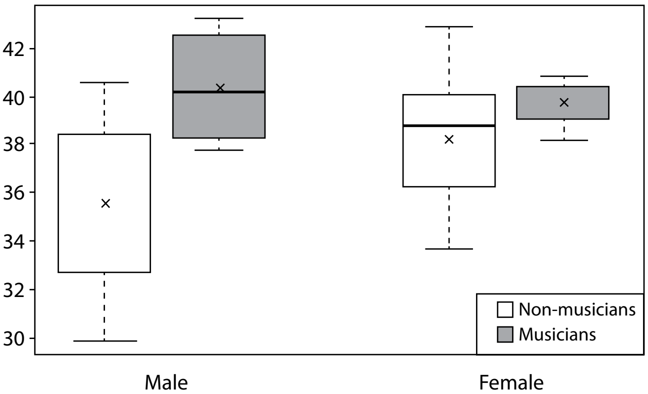

Fig. 3. Relative volume of gray matter in male and female non-musicians and musicians, % of total brain volume.

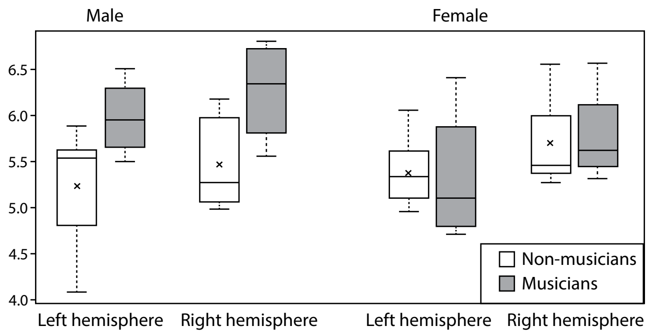

Fig. 4. Volume of superior temporal gyrus in musicians and non-musicians, cm³.

This study showed that the volume of several cortical structures in the brain of male and female musicians was bigger than that of male and female non-musicians, respectively. Median volume of the opercular region of Broca's motor speech area in the inferior frontal gyrus of the right hemisphere (RH) was 2.53 ± 0.94 cm^3 and 2.82 ± 0.10 cm^3 in male non-musicians and male musicians, respectively. Male musicians had the same trend in their brain LH. Median volume of the opercular region of Broca's motor speech area in the LH was 2.42 ± 0.62 cm^3 and 2.72 ± 0.09 cm^3 in male non-musicians and male musicians, respectively.

Hippocampus volume was slightly increased in musicians (p = 0.57), and median hippocampus volume in the RH was 3.25 ± 0.19 cm^3 and 3.32 ± 0.36 cm^3 in male non-musicians and male musicians, respectively.

Of note are changes in the volume of cortical structures in the temporal region of the brain in male musicians compared with these brain structures in non-musicians (Fig. 4). Median volume of the superior temporal gyrus in the RH was 5.27 ± 0.88 cm^3 and 6.34 ± 0.72 cm^3 in male non-musicians and male musicians, respectively (p = 0.048). Median volume of the superior temporal gyrus in the LH in male

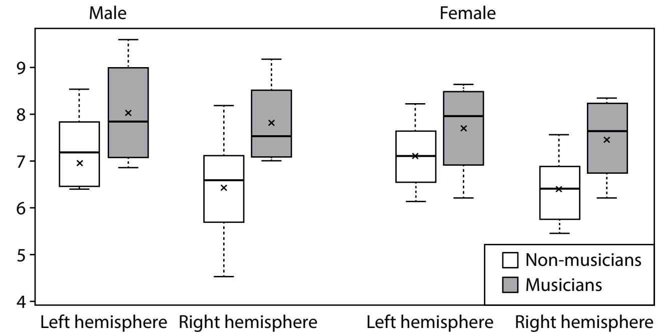

Fig. 5. The volume of the upper parietal lobule of the brain of musicians and people of the control group, cm³.

musicians (5.95 ± 0.45 cm^3) was also higher than in male non-musicians (5.53 ± 0.73 cm^3) (p = 0.110). In women, median volume of the superior temporal gyrus in the RH was 5.63 ± 0.38 cm^3 and 5.46 ± 0.62 cm^3 in female musicians and female non-musicians, respectively (p = 0.604). Median volume of the superior temporal gyrus in the LH was 5.10 ± 0.77 cm3 and 5.32 ± 0.51 cm^3, respectively (p = 0.604).

A trend towards an increased volume of the superior parietal lobe was shown in musicians (Fig. 5). Median volume of the superior parietal lobe in the RH was 6.58 ± 1.33 cm^3 in male non-musicians and 7.58 ± 2.20 cm^3 in male musicians (p = 0.072); that in the LH was 7.21 ± 1.40 cm^3 and 7.89 ± 1.61 cm^3, respectively (p = 0.368). In women, median volume of the superior parietal lobe in the RH was 6.40 ± 1.19 cm^3 and 7.71 ± 1.19 cm^3 in female non-musicians and female musicians, respectively (p = 0.076). In the LH, median volume of the superior parietal lobe was 7.14 ± 1.16 cm^3 and 8.04 ± 1.18 cm^3 in female non-musicians and female musicians, respectively (p = 0.330).

This study demonstrated increased thickness of the cortex in several cortical structures in musicians. For example, median cortex thickness in the angular gyrus of the brain LH was 2.04 ± 0.29 mm and 2.20 ± 0.19 mm in male non-musicians and male musicians, respectively (p = 0.283). A similar increase in median cortex thickness in the angular gyrus was seen in male musicians (2.30 ± 0.18 mm) *vs.* non-musicians (2.13 ± 0.23 mm) (p = 0.048). Median cortex thickness in the angular gyrus in female musicians was also higher than in female non-musicians (p = 0.017 and p = 0.034) with the differences being statistically significant in both hemispheres, while differences in men were statistically significant only in the RH.

There was a trend towards increased cortex thickness in the superior temporal gyrus (lateral) of the LH in male musicians (2.68 ± 2.68 mm) *vs.* male non-musicians (2.42 ± 0.30 mm) (p = 0.109); that of the RH was 2.71 ± 0.11 mm in male musicians and 2.38 ± 0.22 mm in male non-musicians

(p = 0.073). In female non-musicians, median cortex thickness in the lateral part of the superior temporal gyrus was 2.55 ± 0.33 mm (LH) and 2.66 ± 0.18 mm (RH); in female musicians, median values were 2.63 ± 0.18 mm (LH) and 2.70 ± 0.27 mm (RH), respectively (p = 0.504 and p = 0.904).

We also showed changes in the volume of the *planum temporale* in musicians. Median volume of the *planum temporale* in the LH was 1.84 ± 0.19 cm^3 in male musicians and 1.60 ± 0.39 cm^3 in male non-musicians (p = 0.214), that in the RH was 1.71 ± 0.18 and 1.41 ± 0.17 cm^3, respectively (p = 0.048). In female musicians, median volume of the *planum temporale* was 1.62 ± 0.39 cm^3 and 1.57 ± 0.20 cm^3 in LH and RH, respectively. In female non-musicians, median volume of the *planum temporale* was similar: 1.45 ± 0.12 cm^3 (p = 0.604) and 1.42 ± 0.17 cm^3 (p = 0.199) in the LH and RH, respectively.

Discussion

Our study showed major differences in the brain structure in musicians *vs.* non-musicians. Increased volume of several cortical structures was found in both male and female musicians.

Our data are consistent with several experimental studies that clearly showed that constant training and mental activities can lead to changes in the structural organization of the human brain and increase the overall volume of cortical structures [15].

Musicians who play the piano and achieve great results in their professional life should work hard. According to Andreas Eriksson's theory, it takes at least 10,000 hours of deliberate practice to master a skill. This corresponds to about 3 hours of training every day, i.e. about 20 h every week. This hypothesis was named “a 10,000-hours rule” [13]. Such intensive systematic training and constant practice were shown to result in structural changes in the entire human brain and individual cortical structures. Several studies showed that constant training in people of other professions also led to changes in their brain structure. This was shown in a study to evaluate the brain of taxi drivers in London, which showed an increase in the posterior hippocampus, which is responsible for spatial perception and spatial memory. More experienced taxi drivers were shown to have a larger volume of the caudal hippocampus [16]. Meditation and learning foreign languages were also shown to be associated with changes in the structure of the human brain.

An analysis of changes in different brain regions of musicians compared with male and female non-musicians clearly showed an increase in the volume of the superior temporal gyrus in musicians.

Our data are consistent with other authors' data who also showed increased *planum temporale*, especially in musicians' brain [13, 17, 18].

Some authors showed that the volume of the auditory cortex in musicians was 30% higher than in non-musicians [19].

Publications also showed that absolute pitch had a great influence on restructuring of musicians' brain (plasticity), particularly on changes in the temporal regions. However, famous musicians who did not have absolute pitch, such as Igor Stravinsky and Miles Davis, were also described in literature [13].

A comparative analysis of the brain structure in musicians and non-musicians allowed us to show increases in the superior parietal region both in the RH and LH. This increase may be related to the fact that the superior parietal region is involved in the integration of sensory information and plays a key role in reading music scores [20, 21].

We showed increased volume of the parahippocampal gyrus, especially in the RH, in the brain of musicians *vs.* non-musicians. This can be explained by the fact that the parahippocampal gyrus is involved in the implementation of emotional and speech functions. Some authors showed activation and reorganization of the parahippocampal gyrus, especially in the RH, in subjects who were listening to music [22].

We showed increased Broca's speech motor area in male musicians *vs.* male non-musicians and in female musicians *vs.* female non-musicians. Music lessons were shown to improve speech functions and an ability to process sound signals [23–26]. Some researchers believe that Broca's speech motor area is actively involved in listening to and playing musical works [27]. Functional MRI was used to show activation of the Broca's speech motor area (fields 44 and 45) in people who were listening to any musical work; activation of the premotor cortex (field 6), orbital region of the inferior frontal gyrus (field 47), and superior temporal gyrus (fields 21, 37, and 22) was also seen [28–30]. All these studies confirmed that speech processing and practicing music are closely related, and music was shown to stimulate and improve verbal working memory [31, 32].

Of great interest are our data suggesting increases in the *planum temporale* in male and female musicians compared with male and female non-musicians, respectively. We showed increased volume of *planum temporale*, particularly in the brain LH.

In this study, practicing music regularly was shown to change structural and functional brain organization.

Available data suggest that music, which results in major plastic changes in human cognitive functions, can and should be used in the treatment of several neurological and psychiatric disorders. Music-supported therapy can be effective in post-stroke rehabilitation, motor activity disorders, anxiety disorders, and other disorders [33–36].

Conclusion

Our study, which investigated structural organization of the brain in musicians, clearly showed significant changes in many cortical structures of the brain, which generally contribute to the development of human musical abilities, speech, and cognitive functions.

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