Mini Review

BIOMEDICAL
Journal of Scientific & Technical Research

ISSN: 2574 -1241

DOI: 10.26717/BJSTR.2023.52.008246

Music and the Plastic Brain. How Sounds can Generate Neuroplastic Adaptations

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ARTICLE INFO

Received: June 12, 2023

Published: August 22, 2023

Citation: Mark Reybrouck. How Sounds can Generate Neuroplastic Adaptations. Biomed J Sci & Tech Res 52(3)-2023. BJSTR. MS.ID.008246.

ABSTRACT

This mini-review is about music and the plastic brain. It sketches some recent developments in music and brain studies with a shift from initial localization and morphometric studies to the study of connections and networks in the brain. A major finding is the realization that learning to play an instrument appeals to almost all higher functions of the brain. Special attention is also paid to the plastic changes that result from continuous and sustained musical engagement. These changes can be demonstrated on two scales of evolution—the phylogenetic and ontogenetic scale—, with structural and functional adaptations that manifest themselves both in the short and long term.

Introduction

Ramón y Cajal, founding father of modern neuroscience, described piano playing as one of the most challenging cognitive skills. As such, he was an early forerunner of contemporary brain research, which has gained real momentum, especially in relation to the field of music. There has been a proliferation of studies on music and brain functions during the last few decades, mainly for two reasons: there is the growing realization that learning to play an instrument appeals to almost all higher functions of the brain, and recent developments in neuronal imaging have provided a breakthrough in "in vivo" measurement techniques to map what happens in the developing musical brain. EEG, MEG, ECoG, PET, fMRI, fNIR, DTI, tractography and 3D visualizations are just a few examples of techniques that make it possible to map the functioning of the active brain (Reybrouck et al. [1]).

In addition, strong mathematical and statistical models have been designed from cognitive neuroscience to interpret the multitude of data available. Besides, there has also been a shift from initial localization studies (where are so-called "musical regions" located in the brain?) and morphometric studies (which regions are more highly developed in musicians than in normal subjects?) to studies related to neuroplasticity—the brain's ability to adapt neural circuits as a function of a challenging environment—, both anatomically and functionally. It is an evolution that has yielded interesting insights into functional interaction and communication between distinct areas of the brain, with a provisional culmination in the study of functional connectivity.

Rather than describing the brain in terms of individual areas with specific functions, there is now the growing understanding that the brain behaves as a complex network of functionally and structurally connected regions. Special attention is paid to the plastic changes that result from continuous and sustained musical engagement, as can be observed especially in professional musicians. Research, therefore, has been initially focused on the "performing" aspect of making music, with as main finding that the brains of musicians are different from those of musical laymen. Recent research, however, has shifted the scope of study to include also "listening" in all its forms. It is an important development that focuses not only on mapping the areas involved in the brain, but also on studying the possible effects of the music on the listener.

Two Scales of Evolution: Phylogeny and Ontogeny

Music is a powerful stimulator for the brain. Three aspects mainly matter here: the music, the listener and the specific context. Attending a dance festival, for instance, is of a different nature than listening intently to a fugue by Bach, and the age, gender and personality of the listener also partly determine how we listen and what the music does to us. Musical background and individual learning history also play an important role. There is a big difference between a top pianist like Yuja Wang who hits 40 keys per second and a beginner pianist who struggles to master playing a simple scale. And the same is true for a skilled listener who can name all the notes heard and an unskilled listener who only experiences the music as a diffuse carpet of sound. Yet, some generalizations are possible that transcend different musical genres and individual listeners. They confirm recent insights that intense engagement with music appeals to almost the totality of available brain functions. For instance, a recent meta-study based on fMRI methodology (Pando Naude et al. [2]) mapped the main areas of the brain involved in music perception, music production and musical imagination (Figure 1). It is important to realize that these structures are imparted to everyone at birth, somewhat similar to a standard software package installed when buying a new computer. The question, however, is to what extent we learn to use this innate equipment effectively. It brings us to the question of the nature of musicality and the related question of whether it is innate or learned (nature *vs.* nurture).

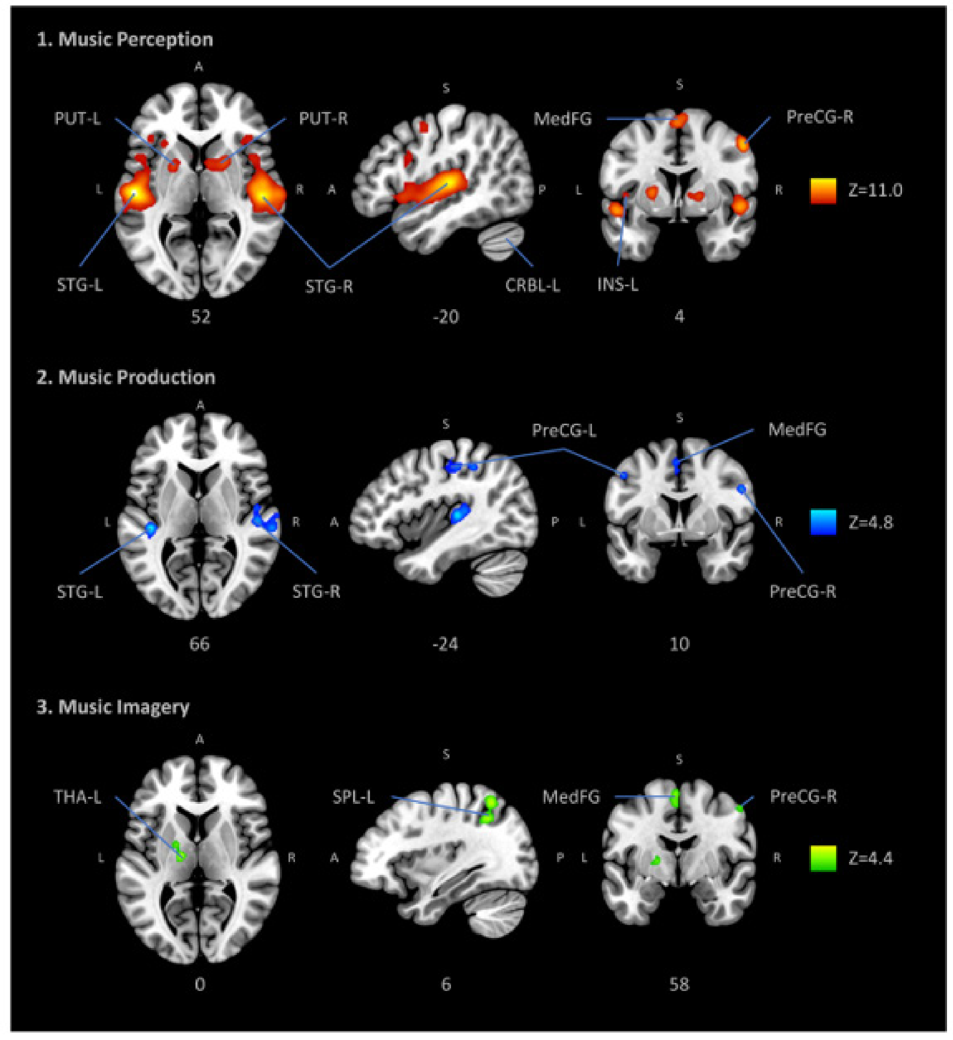

Figure 1: Overview of brain structures related to music perception, music production, and music imagery. The following structures have been identified: cerebellum (CRBL), insula (INS), medial frontal gyrus (MedFG), precentral gyrus (PreCG), primary motor cortex (M1), putamen (PUT), superior parietal lobule (SPL), superior temporal gyrus (STG), primary auditory cortex, and THA thalamus (THA). Reproduced without adaptation from Pando-Naude et al. 2021© Springer, Creative Commons Attribution.

The answer lies in the delicate tension between two levels of description: the broader evolutionary scale of man as a species (phylogeny) and the more limited scale of man in his personal development from newborn to elder (ontogeny). Humans, as higher species, are born with an innate disposition to evaluate their sounding environment in terms of possible danger, as well as opportunities for survival. Listeners—also performers are listeners—react also as biological beings, who rely on a number of bodily systems imparted at birth (Reybrouck et al. [3]). These are primarily our sensory systems, the musculoskeletal system and the nervous system (central and peripheral), each of which can be the object of adaptation: we can learn to perceive better, we can refine our movements, and we can learn to fine-tune the links between sensory input and motor output. This brings us to the field of sensorimotor coupling and integration, which underlies many forms of intelligent behavior.

Neuroplasticity

The brain is the guiding agency in this, and that brain is extremely plastic, as evidenced by the phenomenon of neuroplasticity, which refers to the brain's ability to adapt in response to challenging experiences. It can result from natural development or maturation, but it is also possible to intervene in the development and link it to learning processes. This is evident in musical performance practice, with top musicians figuring as models for the study of skill acquisition and expert behavior (Reybrouck et al. [4,5]). Morphometric changes have been observed in their brains as a result of sustained and persistent training, with at the macrostructural level, demonstrable differences in size of certain subregions, such as the primary motor cortex, the cerebellum, the planum temporale, the corpus callosum, Heschl's winding and the fasciculus arcuatus. The microstructural modifications are at the level of individual neurons and synapses. They aim to increase the efficiency of neural connectivity through the creation of new neurons (neurogenesis), glial cells and capillaries, the strengthening of existing synapses, the formation of new synapses (synaptogenesis), larger axonal branching and growth of dendrites (Bengtsson et al. [6-12]). The combination of macro- and microstructural adaptations leads to some basic mechanisms for the refinement of neural circuits. Music and musicians, therefore, provide a rewarding field for the study of neuroplasticity, with numerous and well-documented changes that are the outcome of training.

They include those brain areas involved in processing auditory information, coordination of swift movements, cognitive control, and mechanisms for coupling between sensory and motor skills, in addition to deeper areas related to the emotional brain (Reybrouck et al. [12]). The overall picture points into the direction of a subtle interplay of cortical and subcortical areas. The changes also seem to be linked to the duration of training, which makes the musical brain a preferred domain for the study of neuroplasticity. This applies primarily to performing musicians, who constitute a unique set of subjects for studying the neurological underpinnings of expert behavior acquisition. The list of skills a performing musician must possess is in fact almost endless. It includes an amalgam of perceptual, motor, interoceptive and emotional skills such as enhancing auditory perception, sensorimotor integration, learning and memorizing motor patterns, fine motor control, storing proprioceptive memory, deciphering music notation and translating it into a performance, focusing attention on reading and playing, listening to and predicting self-produced sounds, and communicating emotions through those sounds (Reybrouck et al. [5]).

These preliminary findings are promising: musical training leads to structural adaptations within the auditory and motor regions of the brain, to an enhancement of functional coupling between these areas and to a stronger expansion of the white matter in a number of conduction pathways (corpus callosum, corticospinal tract, fasciculus arcuatus) (Reybrouck et al. [12]). However, neuroplasticity is not restricted to performance musicianship. Listening also can lead to plastic changes, and this both in the short- and long-term, with enhanced functional links between several areas of the brain. Attentive listening to music is, after all, very challenging. It appeals to several types of memory, in addition to attention, content processing, target detection, and motor induction.

Clinical and Therapeutical Applications

The neuroplastic effects of music manifest themselves on two-time frames: short-term and long-term. The long-term effects are the easiest to map objectively because they can be demonstrated on the basis of "structural" adaptations (histological and morphometric studies). Thorough musical training, however, can also lead to stronger "functional" links between different areas of the brain. For instance, greater connectivity can be demonstrated between the auditory cortex (superior temporal gyrus) and the reward system (medial prefrontal cortex, insula anterior, and nucleus accumbens), and between the front and back of the brain (fasciculus arcuatus). In this sense, it is now assumed that there is a coupling between those brain regions involved in aesthetic judgement, moral judgement and the reward system. However, this coupling is not innate but must be acquired. The bottom line is that skilled listeners can fall back on a different wiring and their modified neural circuits can effectively influence their way of aesthetic enjoyment. It is a way of interacting with music that manifests itself as a greater receptivity to its intrinsic qualities, and it is the object of the recent field of *neuroaesthetics* (Brattico [13,14]). The short-term effects on the other hand are mostly traceable to the physiological effects of the music, with a direct influence on basic and vital functions such as respiratory rhythm and depth of breathing, heart rate, blood pressure, electrodermal activity, intensity of muscle tone, brain activity with modification of specific frequency regions (brain waves), and changes in blood level concentrations.

These changes are barely noticed but are largely responsible for the actual enjoyment of the music. The findings open up a new field of research that links music perception to affective neuroscience and the neurochemistry of emotions. Music is thought to be partly responsible for the release of chemical substances that have a direct impact on endocrine function with a very delicate balance between the so-called happiness hormones (dopamines, oxytocin, prolactin) and stress hormones (cortisol). The findings are not yet conclusive, but they provide important clinical perspectives. After all, musical enjoyment involves the production of "the body's own opiates," (endogenous opiates) as opposed to the invasive applications of medicine and pharmaceuticals that often use "foreign substances." There is a growing understanding that the choice of music is not unimportant in this context, and the same holds for aspects related to the personality type of the listener. Music that sounds too loud excites the sensory system outside the zone of optimal excitation, but listeners who are looking for kicks and strong stimuli (sensation seekers) may constantly challenge the physiological default values of their homeostatic balance (Reybrouck et al. [15]). In this sense, music can be considered as a potential stressor, with listening being experienced as an allostatic load, which is the cumulative effect of wear and tear resulting from non-optimal stimulation on the body's organs and tissues.

Much research has already been done on the potentially harmful effects of too-loud and acoustically distorted music (hearing damage, disruption of hormone balance, sclerosis of connective tissue structures, etc.), which has been grouped under the umbrella term of vibroacoustic disease (Reybrouck et al. [16]). However, this allostatic load need not always be negative. There is also the concept of "optimal allostatic load", with the related distinction between eustress and distress (Selye [17]). The latter is the stress, which is perceived as taxing, the former provides just that extra stimulus that allows us to perform better, due to an increased degree of activation. It is a phenomenon that is easily recognized by surgeons when successfully performing a delicate and life-threatening operation, and the same applies to professional musicians who control their stage anxiety and perform better just because of those extra stimuli. Many of these effects take place at a pre-conscious level. It is possible, however, to get to grips with them, and even to intensify and refine these basic processing mechanisms through education or training. It opens up a new field for clinical applications to adjust the wiring, connectivity and neurochemical processes towards a better functioning of the brain through intensive listening training and active music-making. Recent research, indeed, has shown that intense and long-term sustained engagement with music not only has a short-term effect on our mood of the moment, but can also generate lasting effects.

The overall picture that emerges is one of complex and widespread activity in the brain, which is the result of training, prior exposure, personal preference, emotional involvement and numerous other modulating factors that relate both to our cultural background and our biological disposition. Our brain, then, is modelled as a result of interactions with sounding music at many levels. Thus, there is not only the performing aspect, when we sing or play an instrument, but also the domain of music listening and mentally representing the sounding music. It is an approach that opens perspectives for broader applications of the effects of music on our physical and psychological functioning with a possible transition from an instantaneous state of wellbeing to an acquired dispositional trait, in the sense that changing our neural "hardware" also affects how we interact with music and our broader wellbeing.

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ISSN: 2574-1241

DOI: 10.26717/BJSTR.2023.52.008246

Mark Reybrouck. Biomed J Sci & Tech Res