Mozart in Us:

How the Brain Processes Music

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Abstract—The increase of studies on brain activity during music listening and processing has generated a puzzling, and in many instances contradictory, variety of findings. Besides methodological reasons, e.g., different brain imaging procedures and the nature of applied stimuli, other factors must account for the observed variety. The objective of the present paper is to illustrate individual factors influencing brain networks during music processing. In three longitudinal follow-up studies, changes in cortical activation patterns due to long-term ear training, to short-term ear training, and to piano training could be demonstrated. Among the factors influencing brain activity during music learning, the instructor's teaching strategy and the individual's instrumental training were of importance. The authors propose that neuronal networks related to music processing reflect the individual's auditory biography, i.e., the personal experiences during auditory learning. The authors therefore conclude that in "high-order" musical processing, many and individually connected brain areas underlie music perception. It seems plausible to assume that the increased neuronal connectivity improves cognitive abilities in general. *Med Probl Perform Art* 15: 99–106, 2000.

In recent years, the increasing public interest in brain research has reached the more traditional and conservative fields, such as the arts and music. Newspapers, journals, and television reports address this topic regularly, and books such as Jourdain's *Music, the Brain, and Ecstasy*[1] are, at least in Germany, among the best-sellers. Not only has a broader public become more and more interested in spectacular results of "musicological" brain research, the academic community has concentrated their efforts on the understanding of brain mechanisms underlying music processing. As a consequence, research into the neurobiological foundations of music learning and musical performance has developed dramatically during the last "decade of the brain." New brain imaging methods such as electroencephalography (EEG), the positron emission tomography (PET) procedure, and, recently, functional magnetic resonance imaging (fMRI) opened the possibility to investigate "how our brains think."[2] The new edition of the *Handbook of Music Psychology* refers to this challenge: "Perhaps no other area of music psychology has seen as much advancement since the first edition in 1980 as neuromusical research" (p. 197).[3] The term "neuromusical research" itself hallmarks the new approach to music and music learning in music physiology and music psychology. And confronted with a continuing shortage of public funding of music education, musicians and music educators hope that brain research can provide them with strong arguments against these public pressures.

The aim of the present paper is to give a short update of some basic findings concerning the neuronal networks underlying music processing and—more important—music learning. The main question we address is how brain networks adapt and change due to music training—in other words, how "the Mozart in us" grows up and develops. This review cannot be exhaustive and we decided to focus mainly on some of our own studies. Since some basic facts about brain structures and neuronal plasticity are necessary to understand these investigations, we start with a more general short paragraph about brain organization.

SOME BASIC KNOWLEDGE ABOUT OUR BRAINS

The cerebral cortex is subdivided into functionally specialized areas. These areas can be separated into sensory, motor, and association areas. With respect to information processing, primary sensory or primary motor areas of the cortex must be distinguished from secondary and tertiary sensory or motor areas. Primary sensory areas are directly linked with afferent sensory input from the sensory organs, e.g., the ears or the eyes. Primary motor areas are directly connected with the motor regions in the spinal cord. Secondary and tertiary sensory areas are adjacent to primary areas and process more complex stimulus features. The primary auditory cortex, for instance, mainly processes fundamental elements of music, such as frequency of tones and loudness. In contrast, the secondary auditory cortex is involved in identifying harmonic, melodic, or rhythmic patterns. The tertiary auditory cortex processes complex sound patterns in a piece of music. Besides such a hierarchical processing, which is

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reflected in the increasing complexity of information processing from primary to tertiary cortical areas, parallel processing may occur at the same time: primary, secondary, and tertiary areas receive the same information at the same time, but process different aspects.

Whereas sensory areas in general process only information from one sensory modality, the association areas integrate information from different sensory or motor areas. To illustrate this, the complex behavior during music making is a typical example of sensorimotor integration at the highest level: an expert pianist reading a piano score hears the notation as an auditory representation in his or her (inner) ear and at the same time may feel the sound as a kinesthetic representation in his or her fingers. Such a convergent common neural representation is processed mainly in cortical multisensory association areas.

LATERALIZATION OF MUSICAL FUNCTIONS: MUSIC IS NOT ALWAYS IN THE RIGHT BRAIN

The two hemispheres of the brain are specialized for specific brain functions. However, it must be kept in mind that both hemispheres interact very closely via the corpus callosum and that the information exchange between the two hemispheres is maintained in as short a time as 10 milliseconds! Auditory input from the left ear is processed to a greater extent in the right hemisphere, although the auditory system has a particularly strong interconnection between inputs from the left and the right ears, due to multiple fiber crossings in the auditory pathway. With respect to more complex information processing, the lateralization of linguistic capacities to the left hemisphere in the large majority of right handers (about 97%) and of left handers (about 90%) is a classic example. But the cooperation between the hemispheres in such a complex task is obvious, considering, for example, that prosody of language is primarily processed in the right hemisphere.[4]

The concept of hemispheric dominance and lateralization has changed in recent years. Whereas traditional theories ascribed particular cognitive functions to one hemisphere, for example, music processing to the right hemisphere and calculation faculties to the left hemisphere, the “cognitive strategy,” the way of thinking, has become another critical variable with respect to hemispheric lateralization. The two basic cognitive strategies are frequently referred to as sequential—or analytical, local—processing of the left hemisphere, in contrast to parallel—or holistic, global—processing of the right hemisphere. To illustrate this, listening to a melody in an interval-based manner has to be regarded as an analytical cognitive strategy and seems to be primarily processed in the left auditory areas. In contrast, listening in a contour-based manner has to be considered a holistic way of thinking and is processed to a greater extent in right auditory areas.[5] Since humans are able to switch from one mode of cognition to the other, a static concept of hemispheric lateralization is not appropriate. According to individually acquired cognitive strategies and actual demands, neuronal networks processing the respective music stimuli must be distributed over both hemispheres.

NEURONAL PLASTICITY: THE BASIS OF MUSICAL LEARNING

The wiring of the brain is exposed to a continuous reorganization process. This permanent reorganization process is called “neuronal plasticity.” Every day, we collect thousands of new experiences. The cerebral cortex processes such sensory information, selects relevant parts of it, and stores it as a new “mental representation” of the outer world. One of the most important functions of our cerebral cortex is the ability to accumulate knowledge throughout life in the huge memory system, the basis of the human learning ability. Long-term effects of neuronal plasticity could account for expertise-related differences in brain activation patterns during music processing found with EEG. We conducted an experiment comparing hemispheric lateralizations during music processing in nonmusicians, amateurs, and professional musicians.[6] Subjects had to listen (1) to a melody and decide whether the last tone of the melody was higher than, lower than, or equal in pitch to the first tone, and (2) to two three-note chords and decide which note in the second chord was changed, the upper, lower, or middle. The degree of difficulty of the task was adjusted to the musical abilities of the subjects. In Figure 1, group statistics in the three groups are shown. Obviously, the majority of nonmusicians activate primarily the right hemisphere, whereas musicians to a greater extent activate neuronal networks located in the left temporal and frontal lobes.

According to modern concepts of neuropsychology and cognitive psychology, these expertise-related effects are due to differing cognitive strategies. Musicians tend to analyze melodies in an interval-based manner. Furthermore, they are able to name the intervals mentally using covert speech, which results in an additional activation of the left frontal lobe. In contrast, nonmusicians are restricted to a sort of “feeling” about the melodic contour. In general, cognitive strategies play an important role during mental imagery of music, requiring inner hearing and analytical processing. When musicians are asked to mentally construct retrogrades of short melodies that were presented previously, brain activation appears not only in the auditory cortex of both hemispheres, but also in the visual association areas of the parietal lobe. This is due to the fact that professionals use mental visualization of musical notation to facilitate the construction of the reversal.[7] Besides cognitive strategy and expertise, emotions accompanying music listening influence brain activation patterns. In a recently performed EEG study, positive emotions during music listening produced an increased activation of left frontal and left anterior temporal cortical areas compared with neutral or negative emotions.[8]

THE IMPACT OF MUSIC EDUCATION ON NETWORKS IN THE BRAIN: EFFECTS OF LONG- AND SHORT-TERM EAR TRAINING

To investigate the impact of music education on brain activation patterns, a series of studies was performed in our laboratory. In a first longitudinal experiment in nine 13–15-year-

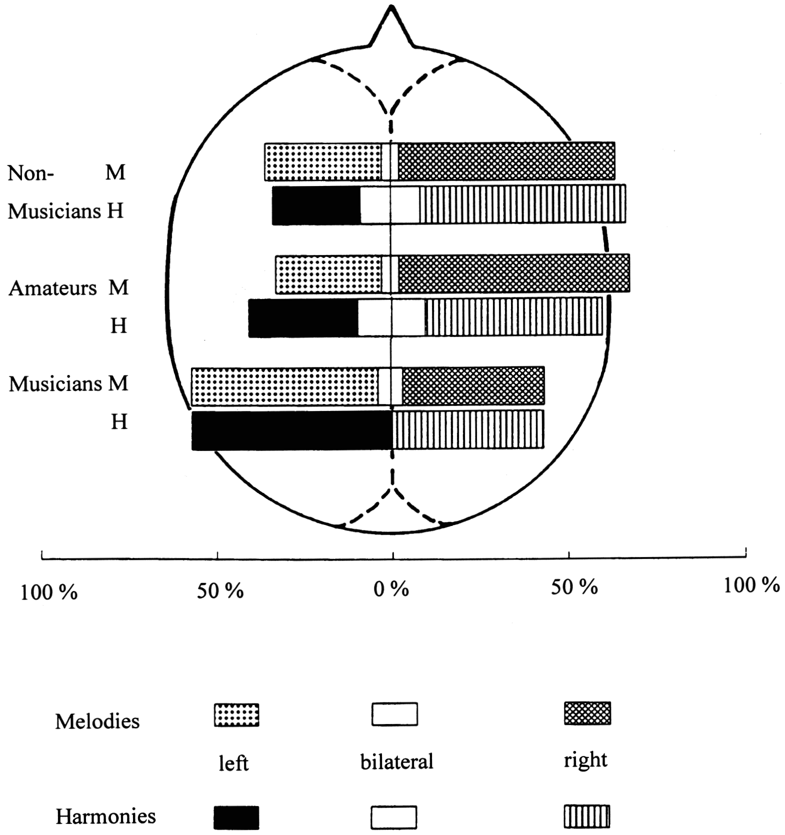

FIGURE 1. Group statistics showing the percentage of predominant left hemispheric (left portion of the bars), right hemispheric (right portion of the bars), or bilateral brain activation during melodic (M) or harmonic (H) music processing. Nonmusicians (*n* = 20), amateurs (*n* = 20), and professional musicians (*n*= 20) were compared.

old students,[9] the purpose was to demonstrate specific changes in auditory brain activation due to musical training, that is, to trace the process of naive listeners becoming expert musicians. The hypotheses were (1) that music learning and acquiring a new mental representation of music change brain activation patterns while listening to music and (2) that different ways of music learning may cause various mental representations that are reflected in different cortical activation patterns.

Brain function was assessed using a newly developed advanced EEG technique. Cortical activation causes an increase in negative field potential at the apical dendrites of cortical pyramidal cells. In Figure 2, a scheme of the measurement principle is shown. The local distribution of these surface-negative low frequency DC potentials reflect cortical activation patterns in various cortical areas. Since these DC-potentials are lower in voltage than the ongoing EEG, the signal to noise ratio has to be enhanced by averaging task-related EEG activity over 30 to 60 trials. This method combines high reproducibility, excellent temporal resolution, and a reasonable spatial resolution at modest costs. The crucial advantages are noninvasiveness, the ability to do follow-up studies, and—in contrast to fMRI—the lack of accompanying noise, which facilitates measurements in the auditory modality.[10]

The task was to judge on formal aspects of symmetrically structured phrases, so-called musical periods that consist of corresponding parts, “antecedent” and “consequent.” Students had to distinguish between correct and incorrect (balanced or unbalanced) phrases. Whereas the antecedent phrase ends in a weak cadence on the dominant, suspending the expected tonic (half-cadence), the consequent phrase leads to a stable ending on the tonic (perfect cadence). This difference in quality of cadences and the balance of the two melodic parts can easily be recognized just by an internal feeling of musical balance and the tension of the cadence.

For training, subjects were divided into three subgroups: (1) A “declarative” learner group received traditional instruction about the antecedent and consequent and their tonal relation with respect to the closing on a complete or incomplete cadence. The instruction included verbal explanations, visual aids, notations, verbal rules, and some musical examples, which were played to the subjects, but never sung or performed. (2) A “procedural” learner group participated in musical experiences for establishing genuine musical representations by singing and playing, improvising with corresponding rhythmic and tonal elements or performing examples from the musical literature. (3) A control group of nonlearners who did not receive any instruction *about* or *in* music. Low-frequency DC shifts of the EEG were measured prior to learning and after a five-week training period.

In Figure 3, the main results of the study are summarized.

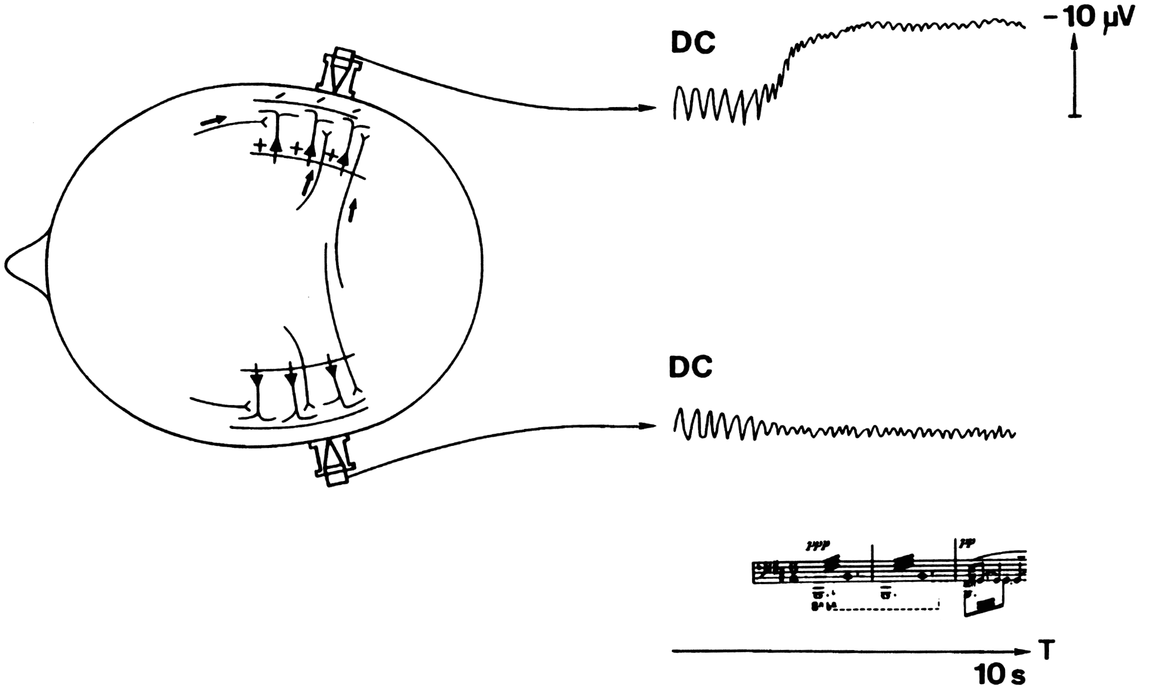

FIGURE 2. Experimental principle of direct-current electroencephalography (DC-EEG): cortical activation is produced by afferent inflow to the cortex. Low-frequency surface-negative field potentials originate from the excitatory postsynaptic depolarization of the apical dendritic layers of cortical pyramidal neurons. Since the pyramidal neurons are oriented in parallel, dipolar field potentials can be recorded noninvasively from the scalp. The increase or decrease in voltage in each electrode position can be quantified and transformed into "brain maps," coding activation dark, inhibition bright, as in Figures 3-5. T = time; s = seconds.

After learning, music processing produced in the verbally trained "declarative" group an increased activation of the left frontotemporal brain regions, which probably reflects inner speech and analytical, step-by-step processing. In contrast, the musically trained "procedural" group showed increased activation of the right frontal and of bilateral parieto-occipital lobes, which may be ascribed to a more global way of processing and to visuospatial associations. These results demonstrate, for the first time directly, that musical expertise influences auditory brain activation patterns and that changes in these activation patterns depend on the applied teaching strategies.

It is clear that there are effects on auditory perception other than those due to weeks or months of training. The ear is able to learn in a very short time period. Among all sensory systems, the auditory system has an outstanding ability to rapidly adapt to new stimulus qualities, an ability based on neuronal plasticity. A performing musician relies essentially on this capacity, for example, when he or she has to adjust his or her playing to a new and unaccustomed acoustical environment. Music students must take a course in "ear training," which usually is designed to improve auditory perception and auditory categorization in 30 minutes.

In order to assess these short-term effects of musical ear training on auditory brain activation patterns, we investigated a group of 32 (16 male, 16 female) right-handed music students who had graduated in piano. The subjects listened to 140 chords and were asked to identify them as major, minor, diminished, or augmented (n = 35 each). During listening and processing of the chords in the "inner ear"—a cognitive operation we like to call "audiation"—brain activation was measured. Subsequently, subjects received either verbally (L1) or musically (L2) based instruction during a single 30-minute teaching session. A third control group read a short story. After the 30-minute training, EEG measurements were repeated and cortical activation patterns before and after training were compared.

Interestingly, training produced various effects. Listening to the chords caused a bilateral frontotemporal activation pattern without a consistent dominance of either hemisphere. The interindividual differences were remarkable. As can be seen in the activation patterns shown in Figure 4, short term ear training produced an increase of overall brain activation with a local maximum over the sensorimotor hand area. In contrast, the control group showed a decrease in brain activity during the second measurement. The brain activation pattern as a whole varied systematically in the two training groups, although local differences were small and did not reach statistical significance. These data indicate that processing of musical chords depends on highly individually developed neuronal networks reflecting the auditory "biography," i.e., the personal experiences during learning. Effects of ear training may be due to an actualization of mental representations acquired during earlier music education. It is reasonable to assume that the actualization of kinesthetic representations of the hand during ear training at the piano accounts for the increase in activity over sensorimotor regions during the second measurement. To prove this idea, we performed the following "piano experiment."

THE PIANO EXPERIMENT: EFFECTS OF PIANO TRAINING ON BRAIN ACTIVATION PATTERNS

It is obvious that exceptional musical performance belongs to the most demanding human sensorimotor skills. Musicians have to perform complex movement patterns requiring high-speed motor control under an unyielding auditory feedback. Furthermore, these movements are closely linked to emotions. A musician wants to express and to communicate his or her feelings on one hand, but may be afraid to make mistakes on the other hand. This "double linkage" to emotions is reflected in the strong reward–punishment system that applies in professional musicianship. The motivation to practice 10,000 hours in ten years during childhood and adolescence as a prerequisite to becoming an expert pianist[11] is based on the reward system. Piano practice means assembling, storing, and constantly improving complex sensorimotor programs by prolonged and repeated execution under attentive control of the auditory system. Many professional pianists report that their own fingers move more or less automatically when they are listening to piano music played by a colleague. In fact, in a cross-sectional experiment, we demonstrated that as a result of many years of practice, a strong, hard-wired linkage between auditory and sensorimotor cortical regions develops.[12] The piano experiment was designed to examine whether, along with proceeding piano training, the establishment of such a linkage can be traced in beginner piano players.

METHODS

The subjects had to perform three sets of tasks on a computer piano that allowed selective examination of auditory and motor aspects of performing: (1) a set of 60 purely auditory tasks with listening to short monophonic piano sequences and 60 right-handed motion tasks with finger tapping on a soundless piano keyboard; (2) a computer-controlled training phase with replaying of acoustically presented short melodic sequences with the right hand on an acoustic keyboard for acquisition of auditory–sensorimotor coupling; and (3) another set similar to no. 1. We hypothesized that after training, listening to piano sequences might cause an additional activation of motor areas, and finger movements on a mute keyboard might cause activation of cortical auditory areas. Brain activation was assessed using 32-channel

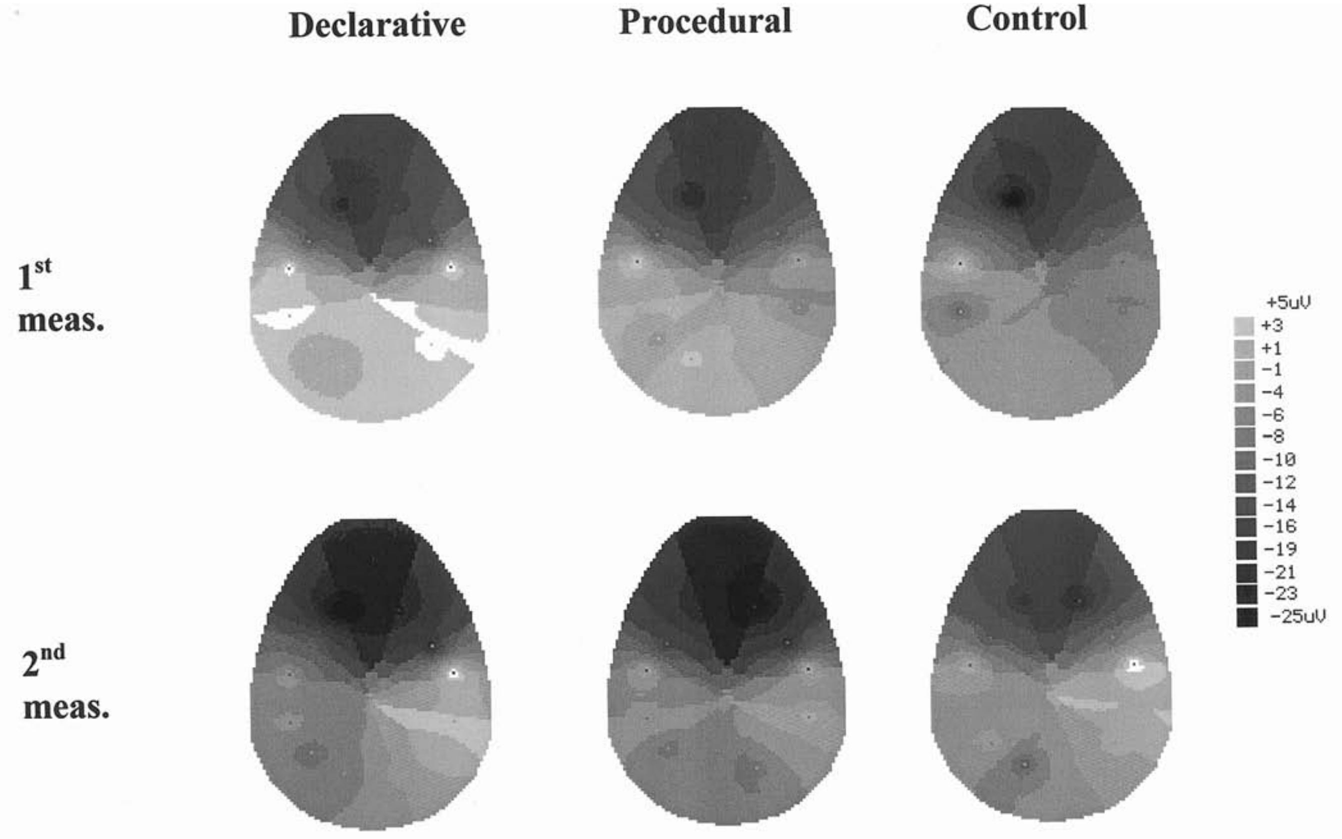

FIGURE 3. Brain maps demonstrating cortical activation patterns before (upper row) and after (lower row) learning in the "declarative" learning group, the "procedural" learning group, and in the control group. Group statistics are shown. Activation is dark, inactivation is white (see microvolt scale on the right). The brain diagrams are shown as top views, frontal regions up, left hemisphere on the left, right hemisphere on the right. As can be recognized, declarative, mainly verbally mediated training leads to an increase in brain activity over the left frontal areas, whereas procedural, genuinely musical training produces an increase in activity over the right frontal and bilateral parieto-occipital regions. In controls, overall activity decreased slightly.

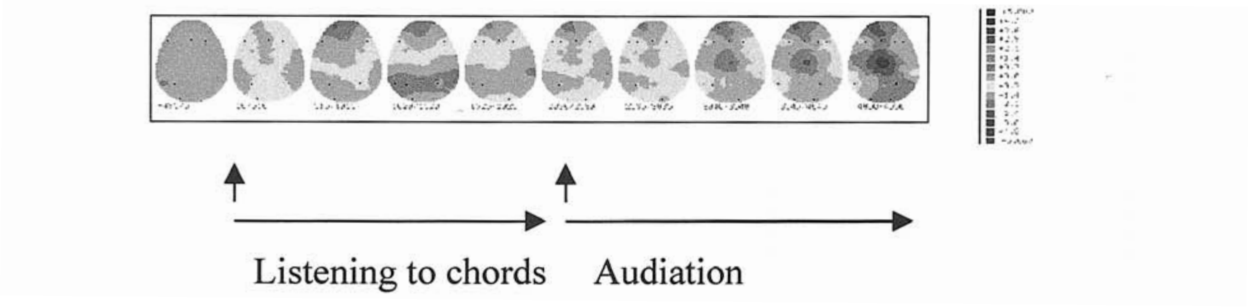

FIGURE 4. Diagrams showing the difference in brain activation after 30 minutes of ear training during listening and audiation of augmented and diminished chords in a group of music students. Same conventions as in Figure 3. Each diagram represents mean activation difference during 500 ms. The general increase (darker regions) in brain activation, locally most pronounced over the central sensory motor regions during the late audiation phase, is statistically highly significant.

DC-EEG during listening and silent finger movements. Activation patterns before and after training were compared using analysis of variance.

Nine right-handed nonmusicians, who had never played an instrument, were trained on a computer piano twice a week over a period of five weeks. The subjects had to listen to short piano melodies of 3 seconds' duration played in the five-tone range and to replay the melodies with the right hand as accurately as possible after a brief pause. An adaptive training algorithm with online performance analysis of the exactitude of the replayed melodies determined the tempo and complexity of subsequently presented targets. In the beginning, the subjects started with very simple three-note melodies. When the replayed melody was correct, the difficulty of the presented melody was increased. After reaching the individual "learning" plateau, the respective training session was terminated. This was usually the case after 15 to 20 minutes of training. In order to ensure that the practiced skill involved only features of auditory-to-sensorimotor integration in the domains of perception, working memory, motor programming, and self-monitored motor execution, no visual or verbal cues such as note names, score notation, or watching their own hands on the piano keys were permitted.

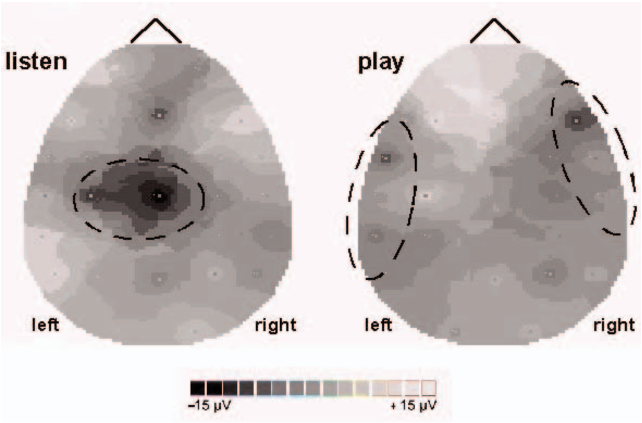

FIGURE 5. Diagrams showing changes in cortical activation after a 10-minute practicing session. Shown is the difference (after–before) in average DC potential. Left: Listening to simple piano tunes; right: Re-playing task with the right hand. Increase of activation is dark; decrease is bright. Note that even after such a short training period during listening, the central sensorimotor regions are additionally active, whereas during finger movements, the temporal auditory regions are additionally activated.

RESULTS

In Fig. 5, the changes in brain activation during the first training session in a representative subject are shown. After 10 minutes of training, listening to piano tunes produced an additional activation of central and left sensorimotor regions. Playing on a keyboard in turn produced an additional activity over auditory regions in both temporal lobes. These early signs of cortical plasticity during the first training session were not stable but stabilized within the subsequent five weeks of training. After ten training sessions a stable coactivation of the auditory and the left sensorimotor hand regions was established. In order to ensure that the subjects did not actually move their fingers while listening to the piano tunes, electromyography (EMG) of the right forearm flexor muscles was recorded and did not reveal any signs of muscular activity. In the movement task the most remarkable effect after five weeks was the development of an additional activation over the right anterior temporal and frontal lobes. Since this area has been demonstrated to be involved in the perception of pitch sequences, this activation might reflect auditory imagery of sounds while moving the fingers on a soundless keyboard. In this context, it should be mentioned that the results of the experiment support the idea of a direct effectiveness of mental training on subtle sensory motor activation patterns represented in the central nervous system.

DOES MUSIC MAKE US SMART?

It seems plausible that an increase in cortical neuronal connectivity as has been demonstrated in novice pianists might improve general cognitive abilities. Many complex mental processes rely crucially on the rapidity of cognitive operations. Therefore, these "neuronal highways" built during music education could increase the speed of information transfer, for example, from one hemisphere to another. Indeed, in adult professional pianists and violinists who started their instrumental training before age 7, the anterior portion of the corpus callosum—the most important interhemispheric connection—is larger than that of nonmusicians or of musicians with later onset of study.[13] Since both violin and piano require subtle bimanual coordination, this phenomenon seems to reflect a specific training-induced structural adaptation, due either to more pronounced myelination of the axons or to preservation of axons that otherwise are subject to the normal developmental loss of nerve fibers, the so-called "apoptotic process."

Surprisingly, "hard data" proving transfer effects of musical abilities on other cognitive domains are rare. Although there are several reports demonstrating a positive correlation between musical aptitude and intelligence in schoolchildren, it is still unclear whether this is a mere coincidence (for instance, due to socioeconomic backgrounds, allowing families with more financial resources to better educate children, to afford expensive musical instruments, and to enable the children to take music lessons) or whether there is a causal relationship. To clarify what we call "intelligence," we refer to Howard Gardner's model of multiple intelligences. Gardner[14] distinguishes seven intelligences: The linguistical, the mathematical, and the spatial intelligences are parts of the usual testing procedures. Furthermore, Gardner names the musical, the motor-kinesthetical, and the intrapersonal and interpersonal intelligences. The two personal intelligences describe the ability of being aware what is going on in one's own mind (intra-personal) and what is going on in another person's mind (inter-personal intelligence).

When reviewing the literature concerning the effects of music education on these seven domains, there are some data supporting the notion of such transfer effects. In a recently published study performed in a Chinese population, musicians had improved verbal memory when compared with nonmusicians.[15] Since in Chinese, as in many Eastern-Asian languages, melodic contour is used for semantic cueing, trained melodic memory in musicians may explain this effect. To our knowledge, in Anglo-German or Roman languages a similar transfer effect has not been demonstrated. Although according to popular belief mathematical abilities are closely linked to musical abilities, there is no scientifically based study demonstrating this. However, when counting rhythms or when organizing fingerings, basic mathematical operations are performed. With respect to spatial intelligence, in recent years public interest focused on the so called "Mozart effect,"[16] demonstrating improved spatiotemporal reasoning after listening to classical music. This effect seems to be rather weak and inconsistent since it could not be replicated by many researchers.[17] But practicing an instrument means in most situations control of body movements in the three-dimensional space. Therefore, we argue that playing an instrument necessarily is linked to a training of spatial abilities, at least with respect to self-referential body coordinates. That musical intelligence is improved by music education is trivial. The transfer of sensorimotor skills acquired during instrumental practice on other movement patterns has not been demonstrated until recently.[18] With respect to the personal intelligences, no transfer studies are available, but it seems plausible that music education may improve insight into the self: when expressing feelings by playing an instrument, the player has to know his or her own feelings. Finally, a chamber music scenario is the best example to demonstrate that musicians need to train their inter-personal intelligence. They have to communicate their feelings, they have to listen to each other, to "give in," to "swing together," to "resonate emotionally." Although scientifically based evidence is rare, we believe that music education and active instrumental playing are intrinsically linked to multiple highly demanding cognitive procedures and therefore might influence and even improve many of the cognitive domains constituting our "intelligence."

GENERAL CONCLUSION: THE MOZART IN US

In this paper we have demonstrated that brain activation patterns during music listening and music processing depend on many factors. Besides expertise, the way of listening—the perceptive strategy—plays a role. Furthermore, music education may change and influence these brain activation patterns in a specific manner. Finally, the individual's learning and listening biography, i.e., the associations connected—"networked"—to the auditory events are reflected in the brain activation patterns. It seems important, for example, whether during ear training the piano is used or the instructors encourage their students to sing. All these factors explain the high interindividual variability of brain activation patterns during music listening. In other words, every individual has his or her own individual networks for music processing. There is not one "Mozart" in our brains, but as many as there are humans in existence—or as the poet Johann Wolfgang von Goethe has expressed it in the words of Homunculus in the drama "Faust" (Part Two, Second Act, scene in the laboratory) in more general terms:

> *Das ist die Eigenschaft der Dinge:*
> *Natürlichem genügt das Weltall kaum;*
> *Was künstlich ist, verlangt geschloßnen Raum.*

In free translation:

> That is the way that things are apt to take:
> The cosmos scarce will compass Nature's kind,
> but man's creations need to be confined.

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