Neurology of musical performance

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ABSTRACT – Performing music at a professional level requires the integration of multimodal sensory and motor information and precise monitoring of the performance via auditory feedback. In the context of Western classical music, musicians are forced to reproduce highly controlled movements almost perfectly with a high reliability. These specialised sensorimotor skills are acquired during extensive training periods over many years. The superior skills of musicians are mirrored in functional and structural plastic adaptations of sensorimotor and auditory systems of the brain. Auditory-sensorimotor integration, for example, is accompanied by rapid modulations of neuronal connectivity in the time range of 20 minutes. Finally, dysfunctional plasticity in musicians, known as musician's dystonia, leads to deterioration of extensively trained fine motor skills. Musician's dystonia may be caused by training induced dysplasticity with pathological fusion of central nervous representations in sensorimotor cortical and subcortical brain regions.

KEY WORDS: brain plasticity, music performance, expertise, sensorimotor integration, musician's dystonia

Apollo's gift: music making as a stimulus for brain plasticity

Performing music at a professional level is one of the most complex human accomplishments. Music, as a sensory stimulus, and is structured along several dimensions. Moreover, making music requires the integration of multimodal sensory and motor information and precise monitoring of the motor performance via auditory feedback. In the context of Western classical music, musicians are forced to reproduce highly controlled movements almost perfectly and with a high reliability. These specialised sensorimotor skills require extensive training over many years, starting in early infancy and passing through stages of increasing physical and strategic complexities.

Sensorimotor skills in musicians are usually automated by many repetitions whereas aural skills are typically refined through a broad variety of listening experiences. Both types of skills are not represented in isolated brain areas, however, but rather depend on the multiple connections and interactions established during training within and between the different regions of the brain. The general ability of the central nervous system (CNS) to adapt to changing environmental conditions and newly imposed tasks during its entire lifespan is referred to as 'plasticity'.

In music, learning through experience and training is accompanied by remarkable plastic adaptations, which are not only reflected in modifications of the brain's neuronal networks, as a result of a strengthening of neuronal connections, but also in its overall gross structure. It is known, for example, that music practice enhances myelination, grey matter growth and fibre formation of brain structures involved in the specific musical task.[1] There are two main reasons why researchers believe that these effects on brain plasticity are more pronounced in instrumental music performers than in other skilled activities. First, musical training usually starts very early, sometimes before age six, when the adaptability of the CNS is highest, and second, musical activities are strongly linked to positive emotions, which are known to enhance plastic adaptations.

This paper will focus on new insights concerning brain mechanisms involved in musical performance and practice. Changes in brain networks and structures accompanying musical achievements, and the neural foundations of training strategies such as mental and observative practice will be discussed. The paper will conclude with the effects related to maladaptive changes of brain networks, resulting in movement disorders such as musician's dystonia.

Wiring the brain: music making as a sensorimotor integration task

Performance-based music making relies primarily on a highly developed auditory-motor integration capacity, which can be compared to the phonological loop in speech production. In addition, somatosensory feedback constitutes another basis of high level performance. Here, the kinesthetic sense, which allows for control and feedback of muscle and tendon-tension as well as joint positions which enable continuous monitoring of finger, hand or lip position in the frames of body and instrument coordinates (eg the keyboard, the mouthpiece), is especially important.

One special quality of musicianship is the strong coupling of sensorimotor and auditory processing.

Practising an instrument involves assembling, storing and constantly improving complex sensorimotor programs through prolonged and repeated execution of motor patterns under the controlled monitoring of the auditory system. Many professional pianists, report that their fingers move more or less automatically when they are listening to piano music played by a colleague. In a cross-sectional experiment, strong linkages between auditory and sensorimotor cortical regions develop as a result of many years of practice.[2] Using functional magnetic resonance imaging professional pianists were asked to listen to simple piano tunes without moving their fingers or any other body part. Figure 1 demonstrates the increase in activation of professional pianists in comparison to non-musicians. There is an impressive activation of the motor cortex demonstrating the sub-conscious or automated auditory-motor co-activation.

Furthermore, in a longitudinal study, it was possible to follow up the formation of such neuronal multisensory connections along with piano training in early pianists. Non-musicians, who had never played an instrument before, were trained on a computer piano twice a week over a period of five weeks. They listened to short piano melodies of a three-second duration played in a five-tone range, and were then required, after a brief pause, to replay the melodies with their right hand as accurately as possible. After 20 minutes of training, first signs of increased neuronal coupling between auditory and motor brain regions were observable. After five weeks, listening to piano tunes produced additional activity in the central and left sensorimotor regions. In turn, playing on a mute (soundless) keyboard produced additional activity in the auditory regions of both temporal lobes.[3] This experiment impressively demonstrates how dynamically brain adaptations accompany these multi-sensorimotor learning processes.

Activation of motor co-representations can occur in trained pianists not only by listening to piano tunes, but also by observing a pianist's finger movements while watching a video. The brain mechanisms of such learning through observation have been clarified in recent years. When monkeys observed the actions of co-species, for example grasping peanuts, exactly the same brain areas were active as if the observing monkeys were performing the action themselves. Additionally, a region in the parietal lobe of the observed monkeys was activated, which is believed to represent the knowledge that 'it is not me who is performing the action'. Quite appropriately, this neuronal network was termed a 'mirror neuron network'. When trained pianists observe video sequences of a moving hand at the piano, the motor hand area in the primary motor cortex, secondary auditory cortices in the temporal lobe and the cerebellum are activated, thus impressively demonstrating such a mirror-system in humans.[4] As a consequence for musical practice, it follows that careful demonstration with the instrument may enhance learning.

Practising through listening and/or observation can be considered as special cases of mental training. Narrowly defined, mental training is understood as the vivid imagination of movement sequences without physically performing them. As with observation of actions, principally the same brain regions are active as if the imagined action is performed; that is, the primary motor cortex, the supplementary motor cortex and the cerebellum.[5] In a study investigating mental training of finger movement sequences of different complexities, brain activation increased along with the degree of difficulty of the imagined motor task. Furthermore, when continuing mental practice over a period of several days, the involved brain regions showed plastic adaptations. Although these adaptations are less dramatic than if the motor tasks were practiced physically, mental training produced a clear improvement in task performance as assessed in finger-tapping tests.

Plasticity of sensorimotor systems: musicians' brains are different

During the past decade, brain imaging has provided important insights into the enormous capacity of the human brain to adapt to complex demands. Brain plasticity is best observed in complex tasks with high behavioural relevance for the individual such that they cause strong emotional and motivational

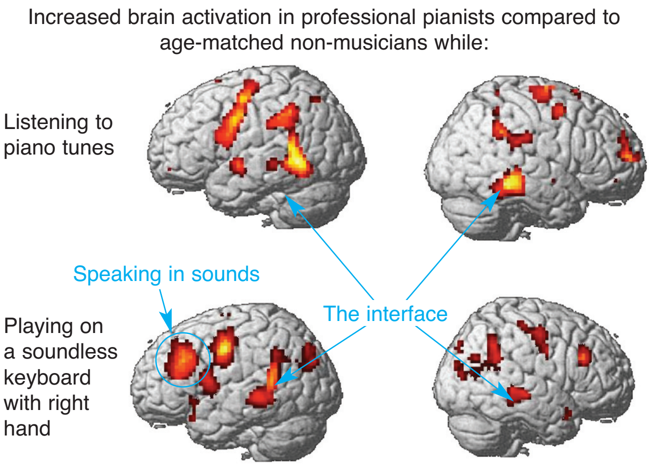

Fig 1. Increased brain activation in professional pianists compared to age-matched non-musicians. Additional brain activity (yellow/red zones) in skilled pianists compared to non-pianists when listening to piano tunes without moving their fingers (upper row), or when moving their fingers on a mute keyboard (lower row). When listening, the primary hand area of the pre-central area is active demonstrating an unconscious co-representation of heard tunes as movement patterns. Furthermore, an auditory association area between the temporal and the parietal lobe is lighting up (blue arrows). This region is similarly active when the pianists are moving their fingers on the mute keyboard. Therefore, this region seems to be an auditory-motor interface, translating the sounds into fingerings and vice versa. Moving the fingers on a mute keyboard (lower row, left) additionally produces an activity in Broca's area. Therefore, this area is not confined to language functions as has been traditionally believed, but also contributes in a more general manner to complex movement patterns which code symbolic communication. It impressively demonstrates that music 'speaks' to our souls. Reprinted with permission from Elsevier.[2]

activation. Plastic changes are more pronounced in situations where the task or activity is intense and the earlier in life it has been developed.

Comparison of the brain anatomy of skilled musicians with that of non-musicians shows that prolonged instrumental practice leads to an enlargement of the hand area in the motor cortex and to an increase in grey matter density corresponding to more and/or larger neurons in the respective area.[6,7] These adaptations appear to be particularly prominent in all instrumentalists who have started to play prior to the age of 10 and correlate positively with cumulative practice time. Similar effects of specialisation have been found with respect to the size of the corpus callosum. Professional pianists and violinists tend to have a larger anterior (front) portion of this structure, especially those who have started prior to the age of seven.[8] Since this part of the corpus callosum contains fibres from the motor and supplementary motor areas, it seems plausible to assume that the high demands on coordination between the two hands, and the rapid exchange of information may either stimulate the nerve fibre growth – the myelination of nerve fibres that determines the velocity of nerve conduction – or prevent the physiological loss of nerve tissue during aging.

It is not only motor areas, however, that are subject to anatomical adaptation. By means of magnetoencephalography (MEG), the number of nerve cells involved in the processing of auditory or somato-sensory stimuli can be monitored. Using this technique, professional violinists have been shown to possess enlarged sensory areas corresponding to the index through to the small (second to fifth) fingers of the left hand even though their left thumb representation is no different from that of non-musicians.[9] Again, these effects were most pronounced in violinists who started their instrumental training prior to the age of 10. In summary, when training starts at an early age (before about seven years), these plastic adaptations of the nervous system affect brain anatomy by enlarging the brain structures that are involved in different types of musical skills. When training starts later, it modifies brain organisation by re-wiring neuronal webs and involving adjacent nerve cells to contribute to the required tasks. These changes result in enlarged cortical representations of, for example, specific fingers or sounds within existing brain structures.

Fig 2. Symptoms of dysfunctional plasticity: typical patterns of dystonic postures in a pianist, a violinist, a flutist and a trombone player. Most frequently, involuntary curling of fingers and compensatory extension of adjacent fingers is observed. In wind instrumentalist, dystonia involves sensorimotor control of the embouchure. Typically in dystonia, no pain or sensory symptoms are reported. Dystonia may afflict almost all groups of instrumentalists but is more frequently seen in the right hand of guitarists and pianists and in the left hand of violinists. Reprinted with permission from Elsevier.[12]

Apollo's curse: musician's dystonia

There is a dark side to the increasing specialisation and prolonged training of musicians, namely loss of control and degradation of skilled hand movements, a disorder referred to as musician's cramp or focal dystonia (Fig 2). The first historical record, from 1830, appears in the diaries of the ambitious pianist and composer Robert Schumann.[10] As was probably the case for Schumann, prolonged practice and pain syndromes due to overuse can precipitate dystonia, which develops in about 1% of professional musicians and in many cases ends their career.[11] Neuroimaging studies point to dysfunctional (or maladaptive) neuroplasticity as one of the relevant pathomechanisms.

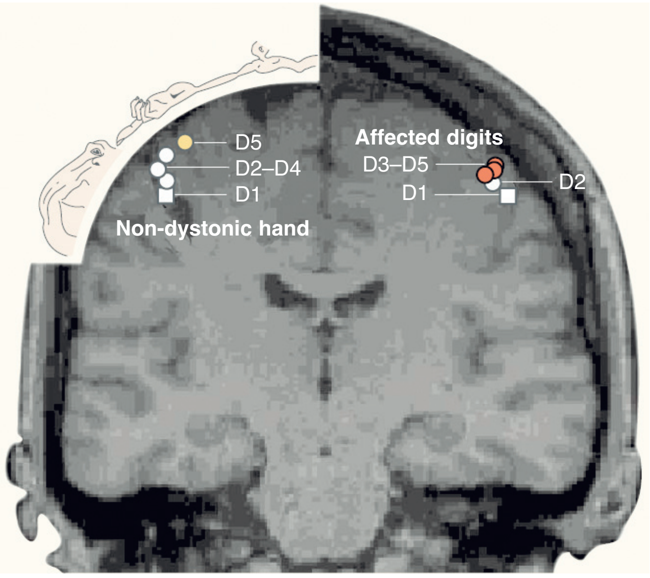

Fig 3. Neuronal correlates of dysfunctional plasticity. Fusion of the somatosensory representation of single digits of the hand in a musician suffering from focal dystonia. The best fitting dipoles explaining the evoked magnetic fields following sensory stimulation of single fingers are shown projected on the individual's magnetic resonance image. Whereas for the non-affected hand the typical homuncular organisation (see inset) reveals a distance of about 2.5 cm between the sources for the thumb and the little finger (white square and brown circle on the left), the somatosensory representations of the fingers on the dystonic side are blurred, resulting from a fusion of the neural networks which process incoming sensory stimuli from different fingers (red circles). Modified with permission from References 1 and 13.

Support for this theory comes from a functional brain imaging study performed in musicians with focal dystonia. Compared to healthy musicians, musicians with dystonia showed a fusion of the digital representations in the somatosensory cortex, reflected in the decreased distance between the representation of the index finger and the little finger when compared to healthy control musicians.[13] An example of a dystonic musician is shown in Fig 3. Such a fusion and blurring of receptive fields of the digits may well result in a loss of control, since skilled motor actions are necessarily bound to intact somatosensory feedback input.

Considering (a) the historical advent of the disorder in the 19th century with rapidly increasing technical demands imposed on musicians, (b) the epidemiological data with rapid and repetitive finger movements as a risk factor, and (c) the neurobiological findings of the blurring of hand representations, it would be tempting to state that focal dystonia finally marks the natural limits of a process of refinement of manual dexterity over a million years. However, hereditary factors with a certain predisposition to develop this condition may also play a role.[14]

In summary, musical performance is an excellent model to study the effects of neuroplasticity in the auditory and the sensorimotor domains. It seems to be one of the most powerful stimuli to drive plastic changes in the CNS. Investigating professional musicians might differentiate the contributions of experience or training from those of genetic predisposition. Studying focal dystonia finally, can illustrate the effects of dysfunctional plasticity due to overuse. An important question arises from the investigations presented here. One has to bear in mind that essential to music is to elicit strong emotional reactions. Shivers down the spine, tears in the eyes, a lump in the throat while listening to music are accompanied by the activation of a brain network which is involved in reward, emotion and motivation. Further research is required to show whether activity in these areas is mediating the powerful effects on neural plasticity.

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