International Symposium on Performance Science
ISBN 978-90-9022484-8

From the Neanderthal to the concert hall: Development of sensory motor skills and brain plasticity in music performance

Eckart Altenmüller

Institute of Music Physiology and Musicians' Medicine,
Hanover University of Music and Drama, Germany

For thousands of years, humans have striven to express and communicate their feelings by singing and playing musical instruments. In order to create new sounds, instruments were invented requiring novel and frequently complex movement patterns. Sensory-motor skills of musicians have some specific qualities: learning begins at an early age in a playful atmosphere. Routines for stereotyped movements are rehearsed for extended periods of time with gradually increasing degrees of complexity. Via auditory feedback, the motor performance is extremely controllable by both performer and audience. These specific circumstances seem to play an important role for plastic adaptations of the central nervous system. Training-induced changes include both brain function and brain structure and can be observed in sensory-motor and auditory networks. However, in the last two centuries increasing specialization and, as a consequence, prolonged training have produced dysfunctional adaptations of the brain, leading to secondary deterioration of movement patterns referred to as musicians' dystonia. This disorder could mark the final point of human evolution of sensory motor skills.

Keywords: brain plasticity; expertise; sensory-motor integration; focal dystonia; evolution

For thousands of years, it has been through the hands of musicians mastering their instruments that humans have communicated and manipulated their emotions. In modern times, we are fascinated by the precise execution of very fast, and in many instances, extremely complex movement patterns, characterizing the skills of professional musicians when performing as virtuosos. When did this faculty develop though? Can musicologists provide an answer to questions concerning the evolution of motor skills by analyzing the degree of difficulty required in musical scores? Are there innate limitations of the central nervous system with respect to the mastery of fast and complex movements? Is there evidence of a shift in human motor accomplishments in historical times? Or, looking at the problem from another perspective, if a time machine had enough space for a Steinway Grand Piano and an expert piano teacher, could an inhabitant of ancient Egypt, given that he is properly instructed during childhood and adolescence, learn to perform the Liszt *B-minor Piano Sonata*?

Sensory-motor skills of musicians in historical times

Definite conclusions about manual skills of musicians cannot be made until the advent of musical notation and preserved witnesses about the quality of the execution of music supplied by contemporaries. In Baroque times, outstanding musicians and performers like Johann Sebastian Bach or Domenico Scarlatti composed extremely demanding music, which in some aspects reach the limits of technical feasibility even for highly specialised virtuoso performers of today. When taking Bach's *Goldberg Variations* as an example, its execution demands exceptional technical skills in some aspects; the rapidity of trills and passages or the precision of bimanual co-ordination for example. However, later performing composers like Liszt—who was an excellent interpreter of Bach's piano music—used these technical refinements as a basis and added further technical difficulties, such as a novel leap and repetition technique to realize his musical visions. In an informative article, Lehmann (2006) convincingly demonstrates the increasing demands on manual skills in musicians over the past three centuries. According to this author, the technical challenges are paralleled by the developments of musical instruments, which in turn in many instances were initiated by outstanding performing composers. An example is the extension of range (number of notes) of the piano. In the eighteenth century alone, the tonal range of the piano grew from four to six octaves. Beethoven requested larger tonal ranges from his piano maker. The same was true for Liszt, who finally arrived at the "modern" range of eight octaves in the nineteenth century. A similar extension is documented for other instruments, such as the recorder, the violin, and the flute. Additionally, innovations in playing techniques of performing composers added complexity to required manual skills. The "third hand" technique for example, developed by the pianist Siegismund Thalberg in the 1830's involves distributing the melody notes between the hands in the middle of the keyboard, while the accompaniment is played in scales and patterns to the left and right side of the melody. This technique destroys not only the classical mapping of hands onto the keyboard with the right hand playing the melody while the left provides the accompaniment, but additionally requires maintenance of dynamic differences between the melody and the accompaniment within one hand, this way imposing heavy skill requirements on the performer (Lehmann 2006).

The increasing refinement of musicians' manual skills during the last three centuries is well documented. However, the question remains whether this improvement is due to early specialization and longer cumulative practice times or whether other factors such as the instructional strategies may have had a crucial impact on the acquisition of manual dexterity. When analyzing the technical skills of child prodigies performing keyboard music in public from the times of Bach until the twentieth century, Lehmann (2006) comes to the conclusion that during this time span acceleration in the acquisition of performance skills took place. In other words, there is a significant tendency for prodigies of more recent generations to play technically more difficult pieces after shorter periods of training than did earlier prodigies. Several factors contribute to this effect. Firstly, over the centuries there is a tendency toward earlier commencement of musical training. Not uncommonly, outstanding contemporary performers start their systematic training at ages younger than six years. Secondly, accumulated procedural knowledge of the most effective teaching methods handed down from generation to generation of performer/teachers may have resulted in an optimization of training methods. Thirdly, due to the specialization of young performers, who focus on only one instrument and neglect other activities, there is increased time spent preparing for performances. Anecdotal evidence for the latter notion is abundant from the nineteenth century on. The pianists Clementi and Czerny are said to have practiced eight hours per day already as children in "solitary confinement" at the piano, Kalkbrenner for 12 hours and Henselt even for 16 hours (Lehmann 2006).

In summary, it is indisputable that the demands on manual skill for the reproduction of composed "serious" music increased continuously from Baroque times until the middle of the twentieth century. It is not only the complexity of movement patterns, but also the elements of tempo, strength, stamina, and the precision of hand and finger movements which constitute this process of increasing perfection over the centuries. Modern society in turn imposes heightened pressures on performers of composed music by comparing the individual live performance in concert with recordings of outstanding peers, easily available on CDs. Additionally, with the possibility of obtaining and splicing multiple takes, studio recordings contribute to an illusionary perfection as standard. All of these changes are reflected in the intensification and prolongation of daily practice. However, one should keep in mind that this development holds only for a relatively small group of musicians, namely the highly specialized classical musicians in the Western cultures of reproducing classical music. The majority of musicians all over the world are either amateur players, playing their instruments in various social contexts, or professionals relying more on improvisational skills (in jazz music, for instance) or on the technical developments of instruments and electronic equipment (for example in rock and pop music).

Brain adaptations accompanying behavioural pressures

Music, as a sensory stimulus, is highly complex and 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 (Walsh *et al.* 2007; Figure 1).

In the context of western classical music, musicians are forced to reproduce highly controlled movements almost perfectly and with high reliability. These specialized sensory-motor skills require extensive training periods over many years, starting in early infancy and passing through stages

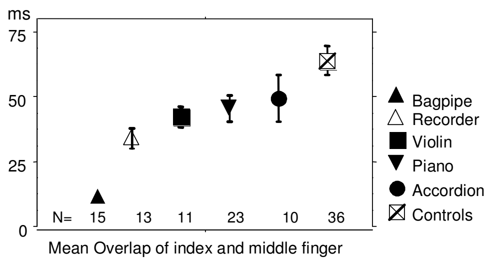

Figure 1. Behavioural adaptations: The role of auditory feedback in a sensory-motor transfer task. Overall averages of a test of synchrony in different groups of professional musicians. The task was to avoid any overlap while touching a metal pad with one index finger and synchronously releasing another finger in a series of trill-like movements which were executed in a standardized and metronome-paced tempo. The pipers clearly have the smallest amount of undesired overlap, followed by woodwind players. The results demonstrate that motor control in musicians is specifically guided by auditory feedback since avoiding overlap is critical in any pipes and woodwind instruments, but not in keyboards and the accordion (bars=±1 SEM; from Walsh *et al.* 2007).

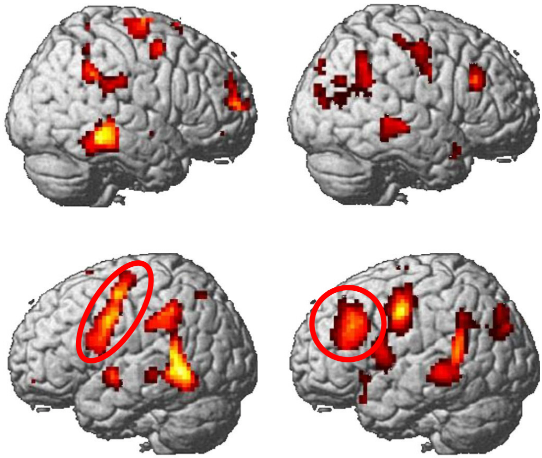

Figure 2. Central nervous adaptations: Auditory-sensory-motor co-representation in a group of seven professional pianists investigated with functional MRI compared to a group of seven non-musicians. The colored spots indicate increase in brain activation in pianists compared to the non-pianists. In the upper row, the right hemisphere is displayed, and in the lower, the left hemisphere. Listening to simple piano tunes (left side) in professional pianists activates the sensory motor areas, especially over the left hemisphere (red circle on the left). Playing simple piano tunes on a silent keyboard activates the left frontal lobe areas (red circle on the right), which are related to gesturing and language processing (modified from Bangert *et al.* 2006, with permission). (See full color version at www.performancescience.org.)

of increasing physical and strategic complexities.

The superior skills of musicians are mirrored in plastic adaptations of the brain on different time scales. At one extreme, years of musical experience, especially in those musicians who begin training early in life, might lead to an increase in grey and white matter volume in several brain regions, including sensory-motor and auditory areas, the cerebellum, and the anterior portion of the corpus callosum. These anatomical alterations appear to be confined to a critical period. The fact that in several of the studies a correlation was found between the extent of the anatomical differences and the age at which the musical training commenced strongly argues against the possibility that these differences are pre-existing and the cause for, rather than the result of, practicing music. At the other extreme, several minutes of training can induce changes in the recruitment of auditory or motor cortex areas, or establish auditory-sensory-motor coupling (Bangert and Altenmüller 2003; Figure 2).

Musician's Dystonia: The final point of a development?

There is a dark side to the increasing specialization 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 (Figure 3). The first historical record, from 1830, appears in the diaries of the ambitious pianist and composer Robert Schumann. As was probably the case for Schumann, prolonged practice and pain syndromes due to overuse can precipitate dystonia, which is developed by about 1% of professional musicians and in many cases ends their career (Jabusch and Altenmüller 2006). Neuroimaging studies point to dysfunctional (or maladaptive) neuroplasticity as one of the relevant pathomechanisms.

Support for this theory comes from a functional brain imaging study performed on musicians with focal dystonia. Compared to healthy musicians, the patients 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 (Figure 4). 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.

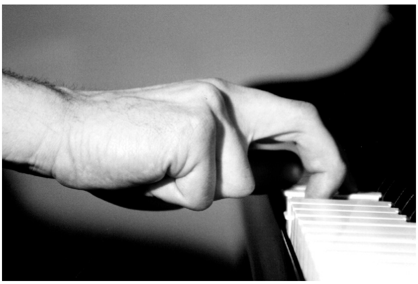

Figure 3. Symptoms of dysfunctional plasticity: Focal dystonia in a pianist. Involuntary flexion of the middle, fourth, and fifth fingers while attempting to play a C-major scale with the right hand. Typically in dystonia, no pain or sensory symptoms are reported. Dystonia may afflict almost all groups of instrumentalists but is more frequently seen in the right hand of guitarists and pianists and in the left hand of violinists (Altenmüller 2003).

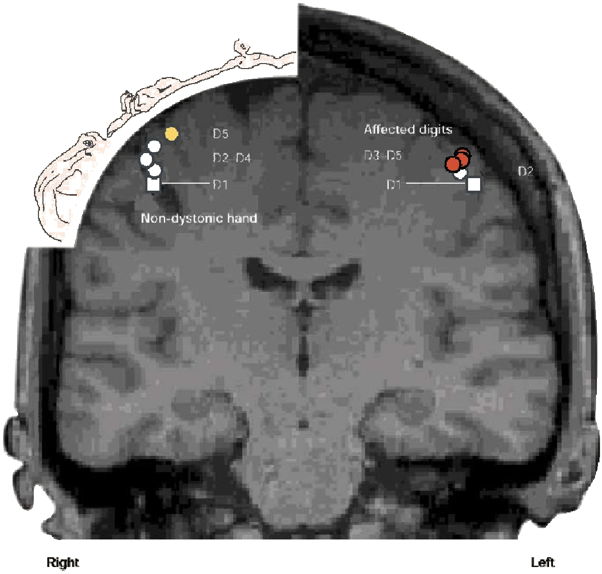

Figure 4. Neuronal correlates of dysfunctional plasticity. Fusion of the somatosensory representation of single digits of the hand in a musician suffering from focal dystonia. The best fitting dipoles explaining the evoked magnetic fields following sensory stimulation of single fingers are shown projected on the individual's MRI. Whereas for the non-affected hand, the typical homuncular organization (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 from Elbert *et al.* 1998 and Münte *et al.* 2002). (See full color version at www.performance-science.org.)

Considering (a) the historical advent of the disorder in the nineteenth 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 above mentioned neurobiological findings of the blurring of hand representations, one is tempted to state that focal dystonia finally marks the natural limits of a process of refinement of manual dexterity over a million years. However, according to a very recent study hereditary factors with a certain predisposition to develop this condition may also play a role (Schmidt *et al.* 2006).

From Neanderthal to Carnegie … and future developments?

Finally, we have to answer the questions raised in the first paragraph. The time machine with the expert piano teacher from a renown German music academy arrives with the Steinway D Grand Piano 3500 years ago in the valley of the river Nil. I have no doubt that the young son of the Pharao, if started at age four with our German professor, could have learned to play the Liszt *Sonata*, given that he was endowed with enough passionate motivation for the approximately 10000 hours of training required, given that he had access to a protein-rich diet to develop large bones, robust muscles, and hands flexible enough to span the tenths.

According to paleo-neurological findings, the brain's structure has not changed significantly in the last 100 000 years. It is highly probable then that humans of the upper Paleolithic period—around 30 000 years B.C.—were able to execute demanding movement patterns when playing on their bone flutes. The true "revolution" which enabled *Homo sapiens* to master novel tasks occurred much earlier in human evolution. It was enabled by the development of *neural plasticity*, the potential to adapt to new environmental stimulation and to new challenges by modification of neural networks, and this potential was most likely present long before the first musical instruments were developed.

As has been demonstrated in the preceding paragraphs, the musicians' brain is an excellent paradigm to study the short- and long-term effects of central nervous neural plasticity and long term adaptation in sensorimotor systems, even in macroscopical brain structures. Furthermore, in the case of focal dystonia, neuroscientists have become aware of the limits of these adaptations under certain stressful conditions.

It is beyond any doubt that creative innovations will continue to be made, but as far as manual skill of the independent use of the fingers is concerned, it seems that a final point in a million-year long development was reached somewhere between the beginning and the middle of the twentieth century. For the piano, the works of late romantic performing composers such as Rachmaninoff, Godowski, Albeniz, and Alcan, with their extension of the Lisztean technique, mark an end point for the age of virtuosos. When comparing the available recordings, contemporary performers do not seem to be essentially superior to the previous generation.

The new challenge in performing compositions of the "classical" modern composers, for example of Messiaen, Boulez, Ligeti, which are all extremely difficult to master, is not based on new demands of manual skill, but rather in their complex musical structure and novelty of rhythmic and harmonic patterns. Since these patterns are as yet usually not integrated in the systematic training of music students, they seem extremely demanding; however, they do not present a new qualitative or quantitative challenge in respect to manual dexterity. Many contemporary composers try to overcome the natural limitations of hand skills by exploiting unusual ways of producing sound, such as plucking the strings in the piano or using the open holes for glissandi in the flute. These new techniques challenge manual dexterity in a new way, but they do not add new complexity to the independent use of fingers as was, for example, the case with Thalberg's third hand technique. Another aspect is important concerning future developments: a majority of music enthusiasts feel uncomfortable when exposed to contemporary music and many of them feel unable to judge the quality of the performance. As a consequence they may have difficulties in perceiving outstanding perfection and will not reward extraordinary manual skills as was the case in earlier times. In other words, society will cease to offer appropriate incentives for performers to study these pieces for months or even years.

After all, I suggest that manual dexterity has reached the end of adaptation—at least in the conventional style of music making. The advent of disorders such as musicians' cramp may well be a warning sign of biological limitations in individuals, who are especially susceptible to disturbances in neural plasticity. It is not only pathology or the maximal available accumulative time of optimal training which limits the "artistic" aspect of musical performance however, it is the fact that society wants to feel *the need to communicate behind the fingers*, the original personal expression of emotional experience. The latter, of course, has to be collected somewhere outside the practice room, limiting the time assigned for manual exercises in a natural way.

Acknowledgments

I am grateful to Hans-Christian Jabusch and Marc Bangert for their most significant contributions to the experimental data reported in this article and for comments on an earlier version of the paper. This work was supported by a grant of the DFG (SPP 1001, Al 269/1-3).

Address for correspondence

Eckart Altenmüller, Institute of Music Physiology and Musician's Medicine, Hanover University of Music and Drama, Hohenzollernstr. 47, 30162 Hanover, Germany; *Email:* altenmueller@hmt-hmt-hannover.de

References

Altenmüller E. (2003). Focal dystonia: Advances in brain imaging and understanding of fine motor control in musicians. *Hand Clinics, 19,* pp. 1-16.

Bangert M. and Altenmüller E. (2003). Mapping perception to action in piano practice: A longitudinal DC-EEG-study. *BMC Neuroscience, 4*, pp. 26-36.

Bangert M., Peschel T., Rotte M., *et al.* (2006). Shared networks for auditory and motor processing in professional pianists: Evidence from fMRI conjunction. *Neuroimage, 15,* pp. 917-926.

Elbert T., Candia V., Altenmüller E., *et al.* (1998). Alteration of digital representations in somatosensory cortex in focal hand dystonia. *NeuroReport, 16,* pp. 3571-3575.

Jabusch H. C. and Altenmüller E. (2006). Epidemiology, phenomenology and therapy of musician's cramp**.** In E. Altenmüller, M. Wiesendanger, and J. Kesselring (eds.), *Music, Motor Control, and the Brain* (pp 265-282). Oxford: Oxford University Press.

Lehmann A. C. (2006). Historical increases in expert music performance skills: Optimizing instruments, playing techniques, and training**.** In: E. Altenmüller, M. Wiesendanger, and J. Kesselring (eds.), *Music, Motor Control, and the Brain* (pp 3-22). Oxford: Oxford University Press.

Münte T. F., Altenmüller E., and Jäncke L. (2002). The musician's brain as a model of neuroplasticity. *Nature Reviews Neuroscience, 3,* pp. 473-478.

Schmid A., Jabusch H. C., Altenmüller E., *et al.* (2006). Dominantly transmitted focal dystonia in families of patients with musician's cramp. *Neurology, 67,* pp. 691-693.

Walsh G., Jabusch H.C., and Altenmüller E. (2007). Synchronization of contrary finger movements in pipers, woodwind players, violinists, pianists, accordionists and non-Musicians. *Acta Acoustica*, in revision.