Music, motor control and the brain
Since the classical treatise by Seashore (1938) on the 'Psychology of music', the lively interest in the relationship between mental operations and performing music has initiated a series of books and symposia dedicated to this topic.

'Brain and music' was part of this inquiry and has been studied since the early years of Neurology. Clinical observations of patients with impairment of their musical abilities such as amusia revealed selective disturbances of music with preserved language capacities or the reverse condition. The correlation with the underlying brain pathology emphasized the differential role of right versus left hemisphere damage in making music. The role of genetic factors for the acquisition of music (Schenker, 1935; 1979) and language (Chomsky, 1968) was highlighted by the long-standing nature versus nurture discussion about the biological roots of these specifically human abilities. Music and the Brain, edited by Macdonald Critchley and R.A. Henson in 1977 gave a comprehensive survey on the state of the art by that time.

Since then, the neuroscientific approach to the study of music has undergone major changes. The advent of brain imaging techniques allowed in vivo examination of the relationship between identifiable lesions and functional deficits in affected patients. Soon after, functional imaging and other advances in non-invasive neurophysiological techniques opened the window for the investigation of functional brain activity during the perception and performance of music. Complementary to this, the behavioural analysis during music performance improved and provided the basis for a quantitative analysis of the spatial-temporal organization of complex movements in music making.

Music, Motor control and the Brain edited by Altenmüller et al. (2006) is a timely survey on recent developments in this field. It elaborates on a symposium held in 2002 at the Monte Verita in Switzerland, a special place where truth has been sought since the late 19th century. The collection of 20 articles is organized in 5 sections on history, psychology, movement analysis, representations in the brain and focal dystonia—a model disorder for maladaptive brain plasticity in musicians. The expertise of the 31 contributing authors covers a wide range from musicology to experimental and clinical neurosciences.

The book starts out with a historical retrospective on how musicians’ performance skills have developed over the centuries. According to the author’s line of argument, the overall abilities have continuously reached higher degrees of perfection and virtuosity, not unlike the observation that world records in athletic sports have been shifted to ever better scores and speeds. Part of the reason for this development is seen in the perfectionism of our times and the pressure through media and recorded music. Further, the complexity of modern music puts higher demands on the apperceptive, mnemonic, and technical skills of performers. Earlier initiation of musical training and higher motivation through better recognition by media and commercial success are regarded as important driving forces to adapt to these affordances. Better material such as high quality strings and other hardware of modern instruments as contributing factors are not part of the discussion.

The next part of the book ('Psychology') highlights aspects of cognition including attention, memory, visuospatial functions, perceptive qualities such as pitch and timbre control and finally the role of central sensorimotor circuits employed in eye–hand and ear–hand coordination. Examining sight-reading shows that musicians use a strategy allowing them to look ahead in the score, thus anticipating the next steps. The eye–hand span measures the advance between the note being looked at and the note being played. This span differs between skilled (2–3 beats) and less skilled pianists (1/2 beat). This difference is surprisingly small and illustrates the gap between such elementary tasks and what seems possible in artistic performances. The great pianist Gieseking was known for eidetic capacities that allowed him to sight-read and memorize a couple of pages and then play it perfectly. Likewise, musicians who have easy access to music apperception by the auditory modality can replay

MUSIC, MOTOR CONTROL AND THE BRAIN
Edited by Eckart Altenmüller, Mario Wiesendanger and Jürg Kesselring 2006.
Oxford: Oxford University Press
Price: £75.00
Hardback
Price: £35.00
Paperback

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Book Review

Brain (2006), 129, 2794–2798 2795

pieces after hearing them. Such anecdotes are in accord with results demonstrating that musical practising operates by a transition of controlled sequencing to automatic processing of larger and larger packages of musical information. Similar to complex speech such as a sermon or lyric, this allows for rapid categorization of domain-specific patterns. Accordingly, highly trained musicians can rely on the translation from musical memory representations into sequential motor ordering, a process not dependent on conscious attention to details of the score. The fundamental role of musical memory and retrieval from memory stores is an important part of this operation. The proportional weight of everyday practice versus musical talent—up to the 'Wunderkind' level—that starts and drives a child to work towards becoming a concert musician remains an unresolved issue that presently seems not easily amenable to scientific exploration.

Some interesting experiments are reviewed that deal with the role of visual and auditory feedback for pianists and brass instrumentalists. The type of skill and the role of feedback are quite different because pitch and intonation control are essential in brass and string but not for keyboard instruments. In the experiments using a piano linked to a musical instrument digital interface, in short 'MIDI', the authors found that the execution of finger movements has a degree of anticipation known as 'negative asynchrony', so that the fingers strike the key a short time before a regular and thus predictable auditory cue.

Experiments on sensory–motor synchronization between external rhythmic cues that can be seen, heard or felt through the mediation of specific sensory cues reveal that synchronized playing is obviously not absolute in performed music. The short intervals between rhythmic cues and the key stroke may commonly last up to 50 ms but this does not seem to cause a problem in the performance because the listener will not appreciate these small shifts. In fact, these shifts tend to become shorter in experienced musicians. The experimental settings for the investigation of optimal synchronization had to be simplified, so that they can only approximate the real life situation of musicians such as playing chamber music in string, wind or brass ensembles, where the requirements for synchronization are probably the highest.

Part 3 ('Movement Analysis') deals with experiments and hypotheses of motor control in musicians based on a number of new and sophisticated methods that allow three-dimensional simultaneous multi-channel recording of hand and finger movements. One may imagine the multiplicity of simultaneous motor control tasks needed to express dramatic tension, pitch control and rhythm for regulating different volumes, and for the modulation of articulation and timbre of the music. Above all, through feedback control, musicians need to be ready swiftly to modify the forthcoming events on the basis of recognizing previously produced deviations from the intended sound, rhythm and intonation. It is common experience that much of this can become automatically controlled upon continuous practice. Since many of the reported data have been derived from MIDI pianos it is possible to analyse the timing of music relative to the recorded movement and formally to show the high degree of evenness in the playing of professional pianists. This is not an easy task, considering the complex fingerings and the alterations in hand and arm position required in rapid passages, in particular with 'thumb under' positions.

Chapter 10 describes in more detail specific motor functions in pianists and string players particularly pointing to the adaptive nature of the central motor system in pianists and the phenomenon of anticipation of certain motor programmes before striking the piano keys. Fingering and bowing in violinists is a bimanual or, better, a bibrachial task of high complexity. As opposed to pianists, there is a different type of movement coordination. For the left (fingering) hand, motor control relates to the need to hit the correct position and rapidly to readjust finger stops if they have failed to produce the intended pitch. Much of the music education of string and of other non-keyboard instrument players is centred on this very task, that is, to achieve a correct intonation. In addition, the bow needs exactly to match the changes in finger stops and in itself reflects multiple physical dimensions including up-and-down speed and pressure of bowing. Well-adjusted physical pressure of the bow hair onto the string while gliding over it is the essence of the tone. The ratio of pressure to bowing speed needs to be rather constant. Increasing the pressure toward the tip and reducing the pressure toward the frog require a high degree of motor control of the bowing arm. Three-dimensional multi-channel recordings of finger and bow trajectories nicely reveal the improved skills as reflected by more even and synchronized movements and tones. They further illustrate the independence of the individual finger movements when playing string instruments. In contrast, finger movements are surprisingly restricted in piano playing where their co-articulated action most likely reflects different mechanical constraints imposed by the different hand position. These limitations in finger control when playing different instruments are not directly compared but their anticipatory compensation indicates the delicate neural control mechanisms. What seems to remain most difficult to assess is the relation between motor and musical aspects. Is there a measurable difference in the individual motor tasks if the music sounds perfect? Moreover, what is the motor substrate when the artist generates emotional expression?

Part 4 ('Representation in the Brain') deals with brain imaging methods employed to identify the brain regions where musical functions are located and how they are networked when performing music. This field of research has undergone the most rapid technical progress over the last years and has opened new avenues for investigating the
The brain–music relationship. From the structural viewpoint, voxel-based morphometry has provided new insights into the question on how far and whether the structure of the brain changes in response to long-term stimulation. The results indeed show persistent representational changes in response to early training. The question whether these adaptive changes single out those areas supposed to be most involved in the specific demands of the given musical practice remains unresolved. Such demand-specific regional changes were seen but were part of a more general increase in overall grey matter volume. Accordingly, the cross-sectional comparison of two groups of children between 9 and 11 years, one of them having 3–4 years of instrumental practice, reveals that the instrumentalists show a significant larger total brain grey matter volume. Moreover, the group trained in a music instrument also outperform the control group in non-musical performance such as vocabulary subtests of the Wexler Intelligence Tests and other tests. This concomitant difference in the performance on cognitive test scores suggests that there exist transfer effects between different domains. Alternatively, different baseline levels of intelligence and motivation (not really taken into account in these experiments) may have confounded the study results. Possibly, both regional music-specific effects and global transfer effects are at work.

Whereas the long-term alterations indicate possible changes of ‘frozen function’—brain structure—the data on functional imaging reveal sites of actual activation or deactivation as they occur in the given experimental condition. By this approach, brain plasticity can be monitored during various aspects of music making.

A central issue of the brain–music relationship is whether it is possible to define a core network for auditory-motor or visuo-motor music processing and performance in musicianship. There are task-specific changes in primary areas such as a larger sensory-motor representation of the left hand of string players in the right motor cortex. But extensive bilateral frontal premotor and parietal activations, as they are known from a variety of sensory–motor tasks, are less specific. It almost seems more difficult to invent test paradigms not activating these areas. Since they can be similarly observed during imagination, preparation and actual execution of playing a musical piece, the relation to the ‘mirror neuron’ network is discussed in several contributions.

The additional bilateral recruitment of the inferior frontal gyrus including Broca’s area and of the temporal cortex shows specific asymmetries that can be modified in various ways. For example, auditory feedback shifts the left hemisphere preponderance during playing the violin without auditory feedback to the right hemisphere. Further, cortical representations appear to change with the respective musical instruments. What seems consistent in several reports is the increase of activity during initial training periods switching to a decrease with further practice.

Comparing musicians and non-musicians, the larger brain areas activated in inexperienced players are contrasted by smaller areas of activation in professional musicians. This is in agreement with experimental data on motor learning and signifies an interesting contrast with the above structural changes. Experimental data on training manual skills in monkeys show smaller neuronal representations of single digits but a finer grain of functional cortical zones indicating gains in the efficacy of microcircuits rather than gross volume effects.

What is interesting when comparing the population-based analysis underlying the MR results with EEG-readiness potential recordings is the high interindividual variability between subjects, most likely reflecting different individual strategies. The neurophysiological methods and the tran-scranial magnetic stimulation discussed in several chapters have two advantages. They allow the study of the sequential evolution of the respective brain activity that can be compared with neurovascular results, thus combining high temporal and spatial information. Further, they can separate excitatory and inhibitory processes, thereby providing better insights into their finely tuned interplay. Disturbances of this delicate balance between excitation and inhibition in response to excessive training seem a key factor in the pathophysiology of focal dystonia (see below).

The following chapter on singing and the correlates of vocal music performance emphasizes the prominent role of the frontoinsular cortex for the control of the midline motor apparatus. The anterior insula is regarded as a centre for speech and coordination of the vocal tract with respiration and swallowing. The dominance of the right hemisphere for pitch processing brings up the question of lateralization of musical versus linguistic capabilities. In singing, both language (the lyric) and music are merged into one performance. Each of the two dimensions can be manipulated independently, requiring a delicate balance in study design.

When using event-related potentials, EEG, MEG and tests such as dichotic listening in presenting spoken or sung linguistic information, there is a trend for musical content processing predominantly in the right hemisphere, while activity evoked by linguistic content is stronger on the left, as one would expect. Yet, the degree of attention is found to be an important denominator: the complexity of the cognitive task induces a higher degree of attention, and this, in turn, leads to a wider spread of activated brain regions with the consequence that the lateralizing effects appear less strong. As noted by the authors, the most telling experiment comparing spoken language, sung language and vocalization has not been done.

The role of song memory is addressed in several studies. It appears that melody helps us encode words. According to the old observation that some aphasics can sing but are not able to speak, training programmes have been developed to regain speech through singing. In an experimental setting, aphasics exposed to songs with the words incorporated, or
to melodies of the same song but with words given along in a spoken way, did not recall words better when they were an intrinsic part of the song. And, aphasics did not produce more words than notes. Therefore, the available data support the notion that singing (with its musical and linguistic content) has separate as well as overlapping regional representations, but in essence it is independent from language skills needed to speak.

An interesting and often overlooked aspect of performing music is that motor tasks need to be started but they also have to pause appropriately. The role of inhibitory neural activity in the fine coordination of acquired finger movements is addressed in a subsequent chapter. Inhibition can now also be analysed by MRI where inhibitory drive can be recognized by negative blood oxygenation level-dependent (BOLD) signals. Along with EEG power spectral analysis and temporary blockade of certain cortical areas by means of transcranial magnetic stimulation, the temporal and spatial features of inhibitory neuronal networks can be elaborated. These are likely to have an impact on the precision of rapid alternating movements in players, and more research is needed into the higher organization of initiating and stopping a learned movement in a musical performance. The complexity increases enormously when the multiple modulatory influences are included, which come through auditory and visual cues, as is the case in ensemble playing.

The final chapters (‘Apollo’s curse—loss of motor control in musicians’) elaborate on disorders of motor control. The main emphasis is on musician’s cramp, a focal, task-specific dystonia, which now has an assumed prevalence of ~1% in professional musicians. In the first chapter, evidence is provided that Robert Schumann suffered from this condition; this may have limited his career as a master pianist in his early twenties. It was the middle finger of Schumann’s right hand that cramped and stiffened during flexion. He constructed several mechanical devices to alleviate the problem but with no or little success. Eventually, he wrote pieces of music that would allow him to exclude the middle finger yet leaving the virtuosity of the others at a very high level.

Medical treatment for musicians’ cramp is now available through Botulinum toxin injected in minute doses into the cramping muscles. This often leads to improvement and may help regain musical skills. The fact that this temporary weakening (paralysing) of muscles may lead to a long-lasting improvement is explained by plastic reorganization (‘resetting’) of the disordered cortical areas, but this process is not well understood. The available evidence on the pathophysiology of musician’s cramp is summarized in detail in another chapter emphasizing that the sensorimotor organization of the hand muscles is changed permanently in this disorder. Unexpectedly, differences in motor programming and cortical activation patterns were identified between musician’s and writer’s cramps. Why this is so cannot be elucidated at present. On the basis of maladaptive plasticity, other types of non-medical treatments are outlined utilizing training protocols based on these observations. The results of these treatments have not yet been validated.

For centuries it has been known that emotional aspects are extremely important for performing music: they drive the musician to study and play a musical instrument or to sing; they provide feelings like excitement; and they create rewards or end in unhappiness depending on success of the performance. Only the chapter about anxiety and stage fright touches the emotional aspects of musical performance.

In an exploratory study, Kesselring undertook a survey in three Swiss orchestras on anxiety and stage fright. Its multi-faceted consequences in motor performance, autonomic regulation and emotional expression are discussed. Several empirical treatment strategies have proved to be useful, including the group of widely used β-(adrenergic) blockers. These drugs need to be tested in prospective treatment trials with read-out measures of physiological, psychological and music performance quality dimensions.

In summary, this book displays a well-balanced account of contemporary neuroscience research into music performance and the role of disordered motor control. The book also shows that new scientific approaches to the study of music and the brain are just at a stage to gain first insights into the processing of elementary aspects of music. Music brings together biological functions like rhythm, emotion and motor skills and the highest levels of human intellectual achievements. Music is an art that lives from what it conveys and what it means to people. David Epstein (1995) emphasized that its symbolic aspects cannot be expressed in terms other than those intrinsic to that art. The contents are untranslatable and specific to the medium in which they exist, so that we can describe and discuss the essence of a work, but cannot penetrate this essence to its core by these secondary means of description. That core remains inviolate, “intrinsic to the medium, the ‘language’, of the work”. Research into the relationship between the fundamental nature of music and specific brain functions has just begun.

**Acknowledgements**

Both authors are neurologists and active amateur musicians (violin playing and singing) with on-stage experience. H.J.F. attended the conference at Monte Verita, but neither of the authors has participated in the preparation or writing of the book discussed in this essay. We thank Ralph Richey for critical reading and helpful suggestions.

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doi:10.1093/brain/awl231
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