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Cortical activation patterns during complex motor tasks in piano players and control subjects. A functional magnetic resonance imaging study

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Abstract

We performed functional magnetic resonance imaging (MRI) in professional piano players and control subjects during an overtrained complex finger movement task using a blood oxygenation level dependent echo-planar gradient echo sequence. Activation clusters were seen in primary motor cortex, supplementary motor area, premotor cortex and superior parietal lobule. We found significant differences in the extent of cerebral activation between both groups with piano players having a smaller number of activated voxels. We conclude that, due to long-term motor practice a different cortical activation pattern can be visualized in piano players. For the same movements lesser neurons need to be recruited. The different volume of the activated cortical areas might therefore reflect the different effort necessary for motor performance in both groups. © 2000 Elsevier Science Ireland Ltd. All rights reserved.

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Neuroimaging studies of cerebral activation patterns underlying the execution of complex motor tasks have established that complex movements require a distributed network of different cortical structures. The primary sensorimotor cortex (SM1) contralateral to the activated extremity has executive functions, the supplementary motor area (SMA) is involved in aspects of motor control including task sequencing, task complexity and movement initiation [6], superior parietal areas (SPA) are activated according to task complexity [19] and premotor areas (PMA) show increased activation during sensory triggered or guided movements [18]. Each motor area therefore plays a specific role in motor control, based on the specificity of its cortical afferents and its efferent projections. The degree of involvement of these areas, however, is still a matter of discussion. Functional imaging studies are inconsistent, with some yielding increased activity within these areas during complex compared to simple movements and others failing to do so [5,17,19]. The heterogeneity of these results might be related, at least in part, to different motor paradigms and different degrees of dexterity, i.e. motor experience of the investigated subjects. There is evidence for an use-dependent functional reorganization in the human cortex in order to conform to its current needs and experiences [2,15]. Long-term motor training such as developing a musical skill should therefore induce changes that might shed light on the interindividual variability of activation within the motor network. We used functional MRI (fMRI) to investigate the involvement of brain areas in the process of generating a complex finger movement in professional piano players and control subjects in order to conduct an individual-based analysis of activated brain areas. The study design allowed us to test whether complex motor tasks lead to different degrees of cortical activation depending on the motor experience of the subjects.

Four right-handed professional piano players (22–51 years, male/female: 2/2, 17–43 years of 4–8 h of training per day) and four age- and sex-matched right-handed controls were included in this study after written informed

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consent was obtained. None had any record of neurological or vascular diseases.

All imaging studies were performed on a 1.5T Philips Gyroscan NT (Philips Medical Systems, Best, Netherlands) equipped with echo-planar imaging capabilities. The subjects were rigidly fixated in a standard headcoil using Velcro-straps and foam padding to minimize motion artifacts. Field homogeneity was optimized for each subject before each scan using an automatic shimming sequence. After localizing images, 10 contiguous 5 mm thick axial T1-weighted spin-echo slices were acquired for anatomical reference which covered the cortical regions of interest (SM1, SMA, SPA, PMA). Functional images were obtained from the same planes using a blood oxygenation level dependent (BOLD) multishot multislice T2* weighted gradient echo EPI sequence (TR/TE/FA: 456/35/45, FOV: 250 × 175, matrix: 128 × 128). In a total scanning time of 3.18 min six alternating epochs of rest and activation each lasting 32 s were performed by all subjects. The scan comprised a series of 72 timepoints (2.7 s/timepoint). Subjects performed a complex finger opposition paradigm using the right (dominant) hand with self-paced light touch of thumb pad to finger pad without looking at the hand. The order of tapping was 5-4-3-5-4-2-5-3-2-4-3-2 (omitting one subsequent finger in each run) and was repeated after completion. During rest periods, subjects were asked to relax. Subjects had sufficient time to practice the task before the scanning session to avoid learning effects during the scan. When an error occurred subjects were asked to start over again. Each subject had to rate the difficulty of the task on a scale from 1 (very easy) to 5 (very hard). Performance during the scanning session was controlled via video monitoring.

Statistical evaluation of task-related hemodynamic changes was performed after motion correction on a voxel-by-voxel basis using the non-parametric Kolmogorov–Smirnov test creating statistical maps that were overlaid on the anatomical T1 weighted scans. Four regions of interest (ROIs) were defined on the anatomical images with respect to the position of cerebral sulci [13]: (1) SM1 with its putative hand representation area, defined by the omega-shaped knob of the central sulcus [20]; (2) SMA, defined as the mesial part of Brodmann area (BA) 6 with the caudal border formed by the depth of the cingulate sulcus; (3) SPA defined as the cortical areas posterior to the postcentral sulcus; and (4) PMA, defined by the precentral and the arcuate sulcus, lateral to SMA [5] (Fig. 1). The number of statistically significant voxels ($P < 0.005$) exhibiting percent signal changes over 2% were summed over the slices in each ROI and averaged over the sets of four subjects in both the piano players and control subjects group. The Mann–Whitney *U*-test was used to look for significant differences in the number of activated voxels between both groups. The significance threshold was fixed at 0.05. As changes in cortical motor areas may be similar across subjects, Spearman rank correlations between the four motor areas (SM1, SMA, PMA, SPA) were computed for the number of activated voxels. As the number of investigated subjects was rather small, we had to pool both groups to account for the otherwise insufficient power of this statistical test.

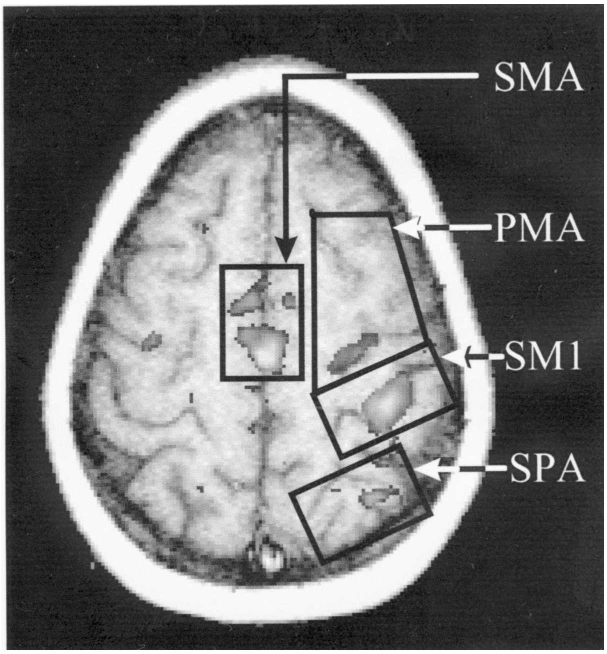

Fig. 1. This figure demonstrates the extent, localization and the anatomical landmarks of the investigated cortical areas in which cerebral activation following a complex motor task was measured. These regions are known to participate in motor processing and were defined based on anatomical landmarks as described in the body of the text. SM1, primary sensory motor cortex; SMA, supplementary motor area; PMA, premotor areas; SPA, superior parietal areas.

Although we did not record task performance using online EMG, we were able to control tapping velocity using the video equipment of the scanner. Piano players had a higher movement rate when compared to the control subjects. Within groups the task was carried out at a similar pace. Performance accuracy was similar between both groups whereas subjective task difficulty differed (piano players, 2.25: control subjects, 3.5). The total number of activated voxels for each subject in every region can be found in Table 1. Fig. 2 shows an example of two slices of an activation study for both a piano player (Fig. 2b) and a control subject (Fig. 2a). For three cortical motor areas (SM1, SMA, PMA) a significant difference between both investigated groups was found ($P = 0.029$), whereas for the SPA no significant difference was present. Fig. 3 shows the number of activated voxels in the different motor regions for all investigated subjects. This diagram reveals, that there was no systematic difference in correlation between the investigated motor areas in both groups (i.e. a large/small SM1 activation was accompanied with a large/small activation in other cortical areas irrespective of motor skills). Therefore we were able to pool the data to perform a corre-

Table 1
Total number of statistically significant voxels (mean percent signal change >2% and a *P*-value < 0.005) following a complex motor task for both control subjects and piano players in the investigated areas and the mean for both groups as determined by functional MRI[a]

	SM1	SMA	PMA	SPA
Control subject 1	49	30	19	12
Control subject 2	29	42	22	8
Control subject 3	63	78	64	34
Control subject 4	38	63	34	51
Mean control subjects	44.75	53.25	34.75	26.25
Piano player 1	17	23	10	1
Piano player 2	9	12	8	7
Piano player 3	23	15	11	12
Piano player 4	14	18	14	4
Mean piano player	15.75	17	10.75	6

[a] For abbreviations see Fig. 1. Piano players have a smaller activated cortical area than control subjects.

lation analysis to test for connectivity between cortical areas irrespective of motor skills. The correlation coefficients calculated for the behavior of the activity in the motor areas were very high for the SMA and the PMA (0.93, $P = 0.001$), for the SM1 and the SMA (0.86, $P = 0.007$) and for the SM1 and PMA (0.86, $P = 0.007$). The correlation of the activity in the SPA with the other motor areas was significant for the PMA (0.74, $P = 0.035$) and the SM1 (0.78, $P = 0.023$), whereas no significant correlation between SPA and SMA (0.61, $P = 0.108$) was revealed.

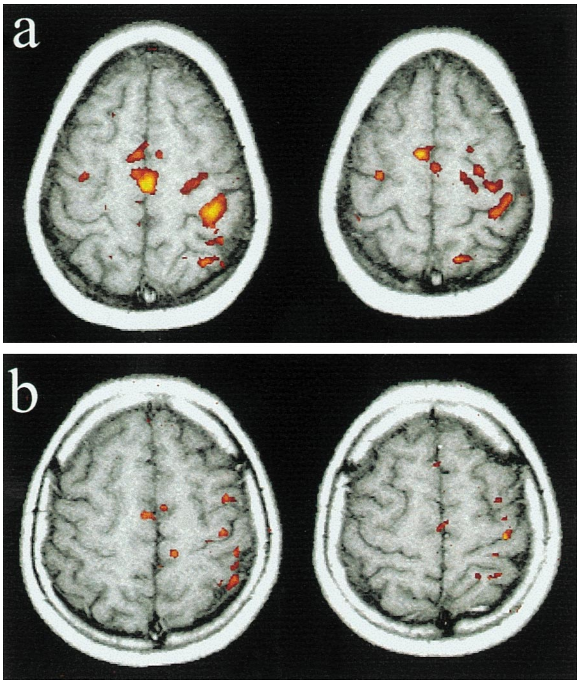

Fig. 2. Functional MRI results of a single control subject and a piano player following task performance. Statistical significance of activation is color-coded on a thermal scale (dark red $P = 0.005$, bright yellow $P < 0.00001$). In (a), two consecutive slices of a control subject (#1) during complex finger movement of the right (dominant) hand can be seen; (b) demonstrates two similar slices of a piano player (#2) during the same task. Slices are oriented according to radiological conventions. Activation patterns in cortical areas involved in motor processing and execution are similar whereas the amount of activated voxels differs between both subjects.

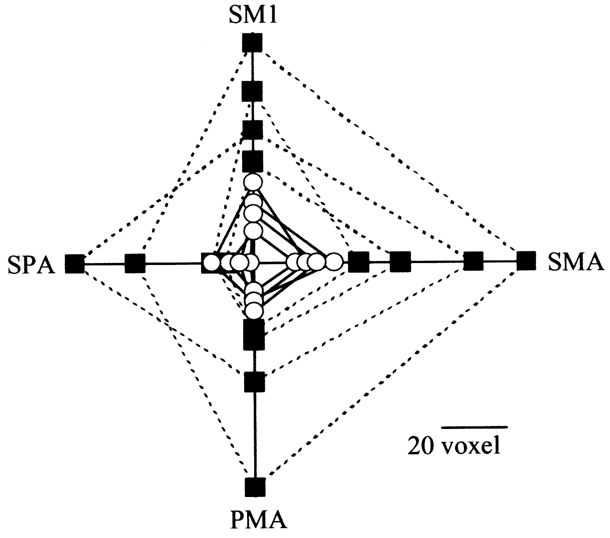

Fig. 3. Star diagram of the number of activated voxels within the different investigated cortical regions for each individual (piano players: open circles and solid lines, control subjects: black squares and dotted lines). Each individual is represented by a quadrangle. If perfect correlation was present, all quadrangles would be of the same shape with differing line-size. For the individual SM1-SMA-PMA triangles, isosceles were found for all individuals indicating a high correlation of those cortical regions: the quadrangles including SPA did not show a common shape indicating a lower correlation of this region with other cortical areas. There was no systematic difference between the piano players and the control subjects indicating that the connectivity between specific cortical regions is similar between individuals regardless of motor skills.

We quantitatively compared task related activity in different components of the cortical motor system in piano players and control subjects. This approach relies on the widely accepted assumption that hemodynamic changes are in accord with the electrical and neuronal activity [11]. Regional CBF changes can therefore be used as an indirect index of brain activity. We chose a complex finger movement task to investigate the differences in cortical activation patterns in the two groups. Different degrees of complexity lead to different cerebral activation patterns. Sadato et al. [14] has shown that complex finger movements recruit a set of brain areas in addition to those areas that are involved during simple tasks. Both electrophysiological [10] and hemodynamic studies [1,17] have shown increased involvement of SMA and SM1 in the preparation and execution of complex motor tasks as compared to simple tasks. Studies employing rapid rate transcranial magnetic stimulation (TMS) indicated that SMA and SM1 are more involved in the processing of complex sequential finger movements than in simple repetitive finger movements [3].

Schlaug et al. [16] found that increased activation of neurons within SM1 is necessary for an increased output to target neurons. Therefore, it may be argued that an increased frequency of finger opposition leads to increased neuronal activity which in turn leads to increased rCBF changes. However, all piano players showed a lesser degree of activation in all movement related cortical subsystems despite the fact that they performed better, i.e. with a higher frequency of finger opposition. This finding suggests an even lesser degree of activation than demonstrated in our study if both groups had performed at a similar speed.

Musical skills, e.g. playing the piano demands orderly, sequential control of individual finger movements, a high degree of bimanual coordination and the ability to develop a cognitive representation of finger movements. When learning to play the piano, visual, proprioceptive and auditory feedback is obligatory. With increasing practice, the pianist does not have to rely on these external cues any longer, movements are slowly refined and the degree of dexterity increases [12]. This stability and fluency in the coordination and execution of complex movements allows the musician to shift attention from mechanical action to artistic performance. In order to adapt to these needs and experiences, functional and maybe even structural changes in the musicians brain are necessary. Data from electrophysiological and hemodynamic functional studies and from structural anatomical investigations have demonstrated the effects of long-term training [7]. Karni et al. [9] found that the cortical representation of the trained sequence in motor related areas does expand. They proposed that motor practice induces the recruitment of additional M1 units into a network representing the specific function. The physiological substrate for the enlargement may be the unmasking of preexisting connections between populations of neurons whose outputs result in different sets of neurons [8]. The final outcome of training is believed to be a more extensive representation of practiced movements in the motor cortex. The primary response to a complex task is recruitment of cells that were less active at lower levels of task demand [19]. In our study, a smaller subset of neurons that control the complex task was recruited for the same performance. For both groups taken together, there was a high correlation between the different motor areas, suggesting functional coupling of the whole cortical network subserving motor activation. This functional coupling was not affected by motor training and thus did not differ between both groups (Fig. 3). This adds to the recently suggested hypothesis [4] that information processing in the motor system is based on network-like cortical activity.

We conclude that, due to long-term motor practice, a use dependent change in activation patterns for cortical motor areas has taken place in piano players. For the same movements lesser neurons have to be activated. It can be assumed that the long-term motor practice in piano players has led to an increase in manual dexterity. Movements that are judged as complex by control subjects therefore have a lesser degree of complexity for piano players. This difference is reflected in the lesser degree of cortical activation.

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