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Short communication

Cortical activations in primary and secondary motor areas for complex bimanual movements in professional pianists

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Abstract

Hemodynamic responses were measured applying functional magnetic resonance imaging in two professional piano players and two carefully matched non-musician control subjects during the performance of self-paced bimanual and unimanual tapping tasks. The bimanual tasks were chosen because they resemble typical movements pianists have to generate during piano exercises. The results showed that the primary and secondary motor areas (M1, SMA, pre-SMA, and CMA) were considerably activated to a much lesser degree in professional pianists than in non-musicians. This difference was strongest for the pre-SMA and CMA, where professional pianists showed very little activation. The results suggest that the long lasting extensive hand skill training of the pianists leads to greater efficiency which is reflected in a smaller number of active neurons needed to perform given finger movements. This in turn enlarges the possible control capacity for a wide range of movements because more movements, or more 'degrees of freedom', are controllable.

Keywords: Musician; Hand motor skill; Magnetic resonance imaging; Motor learning

During motor skill acquisition, movements gain speed, precision, automaticity, and adaptability. These behavioural consequences of motor skill acquisition and practise are often accompanied by considerable neuronal reorganisations both within the primary and secondary motor and sensory cortices. Applying imaging methods such as PET and fMRI, it has been shown that these reorganisations include an initial decrease of activation within the M1 contralateral to the moving hand, which is followed by an enlargement of M1 activation during the course of motor training which is sustained after 4 weeks of training. These changes persist for several months [13]. Additional evidence has shown changed cortical activation patterns within the basal ganglia, the cerebellum, and the parietal cortex during motor skill acquisition. For instance Seitz et al. [18] showed that learning new movement trajectories involves the cerebellum, while overlearned trajectorial movements engage the premotor cortex. A further study by Seitz and colleagues revealed that the kinematic representations of graphomotor trajectories are multiply represented, especially in the human parietal cortex, and that this representation changes during the course of physical and imagined training [17]. Furthermore, it has been shown that during the course of learning visuomotor associations activations within the lateral premotor cortices change substantially [8]. However, all of these brain imaging studies focused on cortical and subcortical reorganisations due to short-term learning of motor skills lasting not longer than 4 months. Effects of long-term motor training of the kind needed to achieve a high standard of performance in playing musical instruments have received little attention. For instance, Elbert et al. [5] demonstrated by means of magnetoencephalography (MEG) that the cortical sensory representation area of the left-hand digits of professional string players is more extended than that of untrained controls. Based on in vivo morphometrical techniques, Amunts et al. [1] showed that the intrasulcal depth of the central sulcus in the vicinity of the hand motor area was substantially enlarged in professional musicians in especially on the right hemisphere which controls the non-dominant hand. These authors claim that the use-dependent functional reorganisation

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reflects the extraordinary patterns of sensory input and motor output that is processed by the individual during development of musical skill. While the latter findings represent more macrostructural adaptations to intensive and long-lasting motor skill training, there are only a few studies available which examine how the reorganised neural assemblies actually control ongoing motor behaviour of different complexities. One exception is a recently published study by Hund-Georgiadis and Von Cramon [9]. They showed increased activation in the contralateral primary motor cortex of non-professional pianists throughout a 35-min finger tapping training. In contrast, activations in secondary motor areas, such as bilateral supplementary motor area, premotor, and cerebellar areas, were low and diminished throughout the training session. The non-musician control subjects showed a different pattern of activation change during the course of tapping training with extensive activation in primary and secondary motor areas in the initial training stage and rapid attenuation in the final stage. A further result of this study was that piano players, although generating higher finger tapping rates than non-musicians, generally displayed less activation in lateral and mesial premotor areas. This suggests that secondary motor areas are less involved in this kind of motor control. Although this work by Hund-Georgiadis and Von Cramon was important in demonstrating that the involvement of primary and secondary motor cortices in learning simple unimanual motor tasks is dependent on experience, there is currently no data available examining cortical activations in skilled musicians during the performance of complex bimanual motor behaviours. The investigation of cortical activation during bimanual movement is important because there is a wealth of data suggesting that the mesial premotor areas are especially involved in the control of bimanual movements. Thus, it might be possible that the lack of mesial motor cortex activation was simply based on the fact that a motor task was used which does not require participation of these motor areas. The present experiment therefore was designed to study cortical activations in primary and secondary motor areas especially during the performance of a complex bimanual motor task for which musicians have been shown to perform more accurately than control subjects, by showing less variability in inter-tap intervals [14].

Four healthy right-handed adults were tested (two men and two women: ages 22–26). All were screened for neurological impairments and were found to be healthy. The subjects were right-handed, as determined by the criterion of consistent right hand preference according to standard handedness questionnaires [15] and hand performance tests [11]. Two subjects were professional classical pianists. Their age at the commencement of their musical training was 5 and 7 years, respectively. Thus both musicians have received musical training for about 17–19 years and they practise on average for about 5–8 h a day. The non-musician control subjects were selected in order to match as precisely as possible to the musicians in terms of age, socio-economical background, gender (one male and one female), hand preference and hand performance, and health status.

There were six experimental conditions:

1. RS/LF: where the left hand tapped twice for each tap with the right hand [left fast (LF)/right slow (RS)]
2. RF/LS: where the right hand tapped twice for each tap with the left hand [right fast (RF)/left slow (LS)]
3. LF: where the left hand tapped at the same rate as LF in the LFRS condition, but alone
4. RF: where the right hand tapped at the same rate as RF in the RFLS condition, but alone
5. LS: where the left hand tapped at the same rate as LS in the RFLS condition, but alone
6. RS: where the right hand tapped at the same rate as RS in the LFRS condition, but alone.

The subjects were instructed to generate their own tapping speed, without undue rapidity under those conditions where fast movements were required. Thus, the tapping was self-paced. The responses were registered by key presses which interrupted an optic fibre light beam. The wrist, as well as all of the inactive fingers (tapping was only done with the index finger), were taped so that they could not participate in the tapping movement. All subjects were first given the opportunity to practice, and this was used to instruct the subjects in the task and to ascertain whether they could perform the task as required. The six conditions were performed in random sequence for each subject. Subjects were instructed to keep their eyes open throughout the scanning series. During the scanning session the room lights were dimmed. In each experimental condition, a series of 85 images was acquired. Each series consisted of multiple periods of ‘baseline’ (OFF, rest), during which the subjects heard only the ambient machine noise but did not perform the motor task, alternating with periods of ‘activation’ (ON, task). During the rest conditions subjects received a constant light via goggles fitted into the head coil. Immediately after switching off this light the subjects were to start the required movement conditions, while switching on the light indicated the start of the next rest condition, during which no movement should be made. The tapping rate was monitored during the scanning session by means of a fibre optic system attached to a laboratory computer to count the taps. Each scanning series began with five baseline images (15-s interval) allowing signal equilibrium to be reached and an initial baseline to be established, followed by 80 images during which ‘activation’ alternated with ‘baseline’ every 15 s (30 s/cycle, 10 images/cycle, 8 cycles). The total duration of each image series was about 6 min.

Functional MR images were acquired using a 1.5 Tesla

Siemens MRI system (SIEMENS Magnetom Vision, Erlangen, Germany), equipped with echo planar imaging (EPI) capabilities and a standard radiofrequency (RF) head coil was used for transmission and reception. Sequences with the following parameters were applied: echo planar imaging EPI, TR=3 s, TE=66 ms, FOV=200×200 mm, α=90°, matrix size=64×64, in plane resolution=3.125×3.125×3.0 mm^3. Using a midsagittal scout image, 16-axial slice positions (0.1-mm interslice gap) were oriented in the anterior–posterior commissure (AC–PC) plane and the uppermost slice was aligned 2 mm below the vertex, thus covering the motor cortex and adjacent motor areas (premotor cortex and supplementary motor cortex). In addition, 3D images of the entire brain were obtained by using a strongly T1-weighted gradient echo pulse sequence (fast low-angle shot) with the following parameters: TR=40 ms, TE=5 ms, 40° flip angle, one excitation per phase encoding step, FOV=25 cm, matrix size=256×256, 128 sagittal slices with 1.25-mm single slice thickness.

Image processing and statistical analysis were carried out using SPM99 software (http://www.fil.ion.ucl.ac.uk/spm). All volumes were realigned to the first volume, corrected for motion artefacts, mean-adjusted by proportional scaling, co-registered with the subject's corresponding anatomical (T1-weighted) image, resliced, and normalised (4 mm^3) into standard stereotaxic space (template provided by the Montreal Neurological Institute [6]) by means of non-linear transformations, and smoothed using an 8-mm full-width-at-half-maximum Gaussian kernel. In addition, the time series of hemodynamic responses were high-pass filtered to eliminate low-frequency components, temporarily smoothed, and adjusted for systematic differences across trials. These adjusted measures were subjected to the statistical analyses. First we performed a group and then single subject analyses. Activated voxels were searched for by using the 'General Linear Model' approach for time-series data suggested by Friston and colleagues [7]. For this, we defined a design matrix comprising of contrasts modelling the alternating periods of 'baseline' and 'activation' and the between-groups differences for this contrast using a delayed box-car reference vector, which accounts for the delayed cerebral blood flow after stimulus presentation. The resulting statistical parametric map of t statistic generated for each voxel was transformed to a map of corresponding Z-values, thresholded at a Z-value of 3.09 (P=0.001, uncorrected for multiple comparisons) and a spatial extent criterion (k) of 10 adjacently (P=0.05, corrected for multiple comparisons) activated voxels. The locus of the activated foci was visually inspected by superimposing the SPM (Z) onto both the anatomical and echo planar images. In order to compare the group results with individual results, regions of interests (ROI) were set up on the M1 and SMAs bilaterally. The SMA was further subdivided into the rostral (pre-SMA) and caudal (SMA proper) parts. Based on the previous review article on the human PET studies [16], the pre-SMA was defined as $-12<x<12$, $0<y<30$, and $45<z<70$, and the SMA proper as$<12x<12$, $-25<y<0$, and $40<z<70$ on the Talairach coordinates. The ROIs for the left and right M1 were defined as a 30-mm cube, whose centre corresponded to the mean location of the peak activation in the M1 across the tasks within each subjects. The volume of these ROIs was 27 ml for the M1 and 18 ml for both the pre-SMA and SMA proper.

All subjects were capable of performing the tasks. The average tapping speeds can be seen in Table 1. The important aspect of these numbers is, first, that tapping rates during the unimanual and bimanual conditions did not differ substantially. For example, the rate for the left hand tapping fast during the right fast/left slow condition was comparable to the left hand fast rate in the unimanual condition. This latter point is important because it avoids a possible confounding of single vs. bimanual task activation patterns with rate effects. However, there are some characteristic differences between piano players and non-musi-

Table 1
Self-paced mean tapping rates in taps/s for the bimanual and unimanual conditions across all subjects[a]

Condition	PP1	PP2	NM1	NM2	PP	NM	NM-PP
Left fast (LF)[b]	2.6	2.9	2.4	2.5	2.8	2.5	−0.3
Right fast (RF)	2.9	2.7	2.8	2.9	2.8	2.9	0.0
Left slow (LS)	1.3	1.2	1.1	1.2	1.3	1.2	−0.1
Right slow (RS)	1.1	1.2	1.2	1.2	1.2	1.2	0.1
RF/LS. right hand[c]	2.5	2.6	2.4	2.6	2.6	2.5	−0.0
LF/RS. left hand	2.7	2.8	2.1	2.2	2.8	2.2	−0.6
RF/LS. left hand	1.3	1.1	1.1	1.2	1.2	1.2	−0.1
LF/RS. right hand	1.2	1.1	1.3	1.4	1.2	1.4	0.2
Ratio[d] right/left for RF/LS	1.9	2.4	2.2	2.2	2.2	2.2	0.1
Ratio left/right for LF/RS	2.3	2.5	1.6	1.6	2.4	1.6	−0.8

[a] Additionally, mean taps/s are given for the pianists (PP1 and PP2) and non-musicians (NM1 and NM2), together with the differences between both groups (PP and NM).
[b] Left hand moving fast at self-paced speed, single hand moving.
[c] Speed of the right hand when right taps twice for each single left tap, bimanual condition.
[d] Ratio of fast tapping hand/slow tapping hand in the bimanual condition (ideal ratio is 2).

cians. First, they tap faster with the subdominant left hand in the unimanual LF condition and in the bimanual RSLF condition probably reflecting superior hand motor skill of the subdominant hand [12].

As can be seen in Fig. 1, all motor areas were significantly activated relative to rest in the bimanual conditions. During the unimanual conditions activity was largely confined to the contralateral primary motor areas. However, analysis of the between-groups differences of the hemodynamic time courses revealed significant differences between pianists and non-musicians, especially for the bimanual conditions (Fig. 2). First, during the bimanual condition where the dominant right hand took the faster rate (RF/LS), there were stronger activations in the left M1 and bilaterally in the pre-SMA for non-musicians. However, when the sub-dominant left hand took the faster rate (RS/LF), non-musicians revealed extended bilateral activations in the mesial motor areas comprising SMA, pre-SMA, and CMA. There were also stronger activations on the right M1, the right inferior parietal Lobule (LPi) slightly extending into the right S1, in the paracentral lobule, and the precuneus area for non-musicians. For the unimanual conditions, we only found stronger activation in the left M1 during the RF condition for the non-musicians, while piano players revealed stronger activation in the precuneus for the same condition. Tapping slowly with the dominant hand exhibited stronger activation on the left pre/postcentral gyrus located in an inferior position ($z=40$ mm) (Fig. 3).

The control subjects showed stronger activation in M1, SMA, and pre-SMA for nearly all movement conditions. For example, during the RF/LS task, the non-musicians revealed a threefold activation on the right M1 as compared to the PP group in terms of the number of activated voxels. A doubling of activation was found on the left M1 during the RSLF task. Besides the finding that the non-

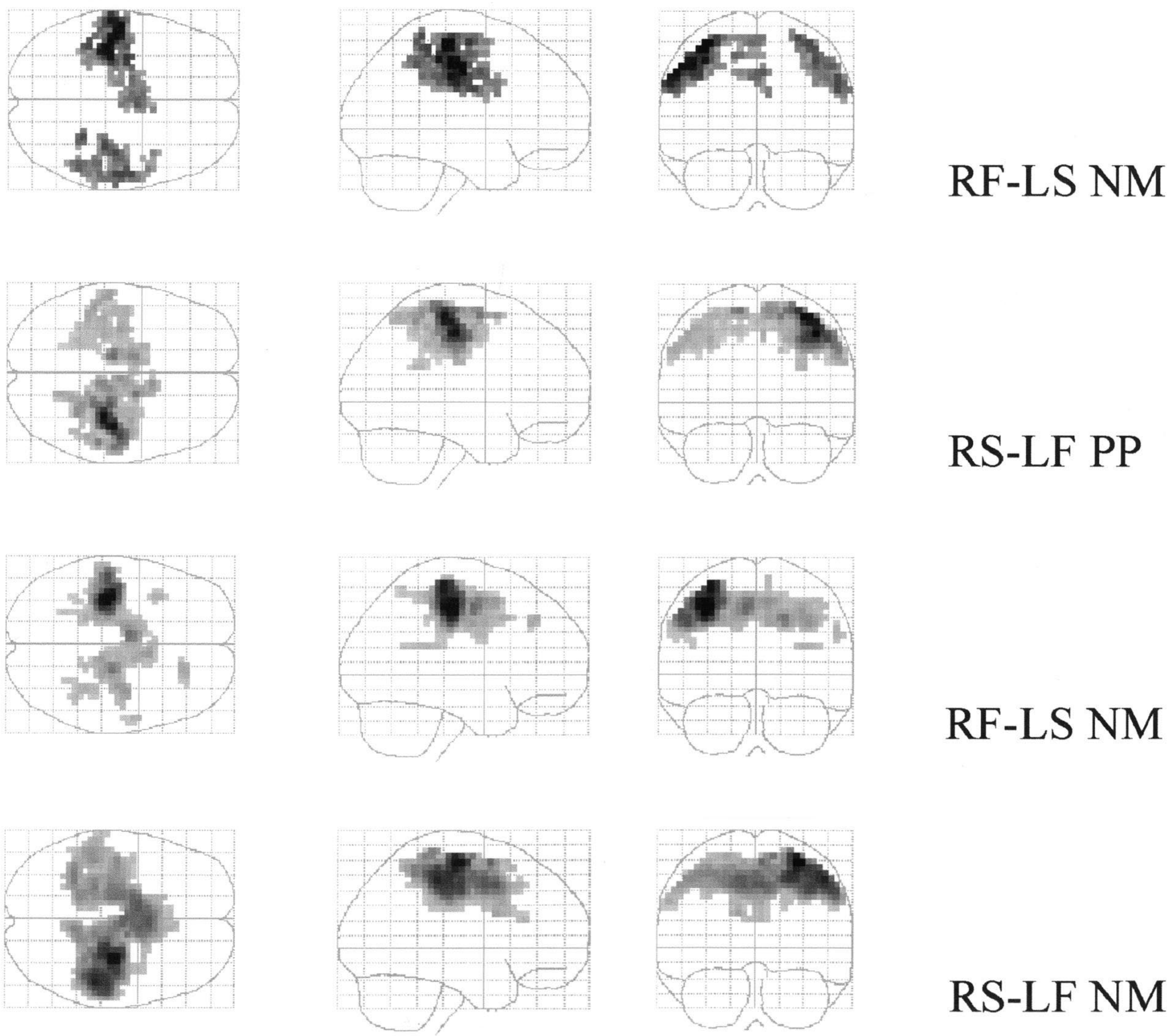

Fig. 1. Cortical activations of the different movement conditions in the group of pianists (PP) and non-musicians (NM) are projected on SPM-projections. The brain projections are viewing the brain from above (transverse, left side on top), right (sagittal), and behind (coronal, left side on the left).

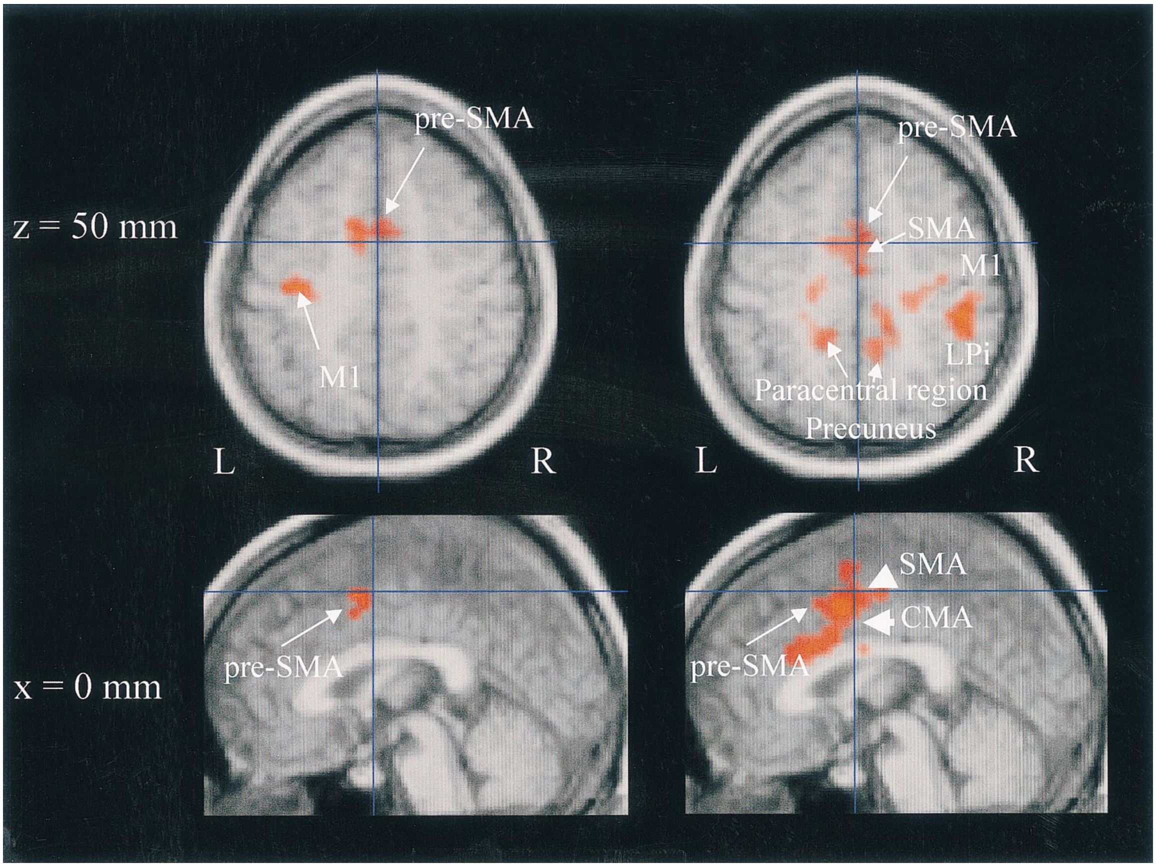

Fig. 2. Functional activations obtained during the bimanual conditions superimposed on the axial and sagittal slices of the averaged T1 images of the four subjects. The horizontal blue line indicates the vertical through the anterior commissure (VAC) and the vertical blue line indicates the interhemispheric gap.

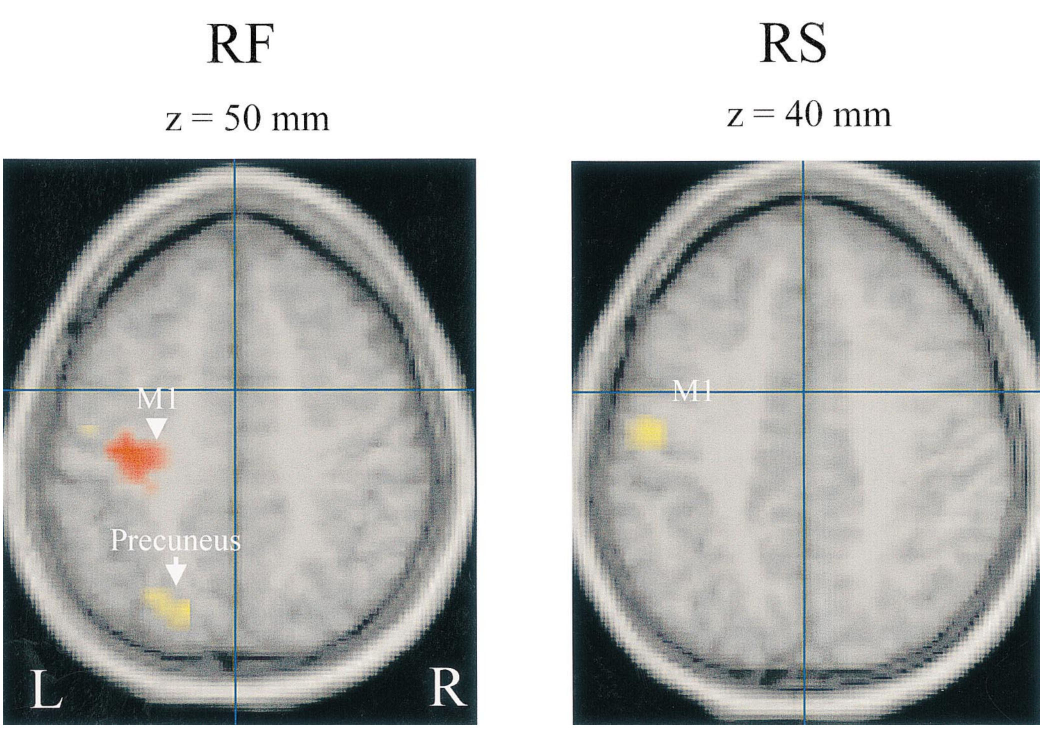

Fig. 3. Functional activations obtained during the unimanual right hand conditions superimposed on the axial slices of the averaged T1 images of the four subjects. The horizontal blue line indicates the vertical through the anterior commissure (VAC) and the vertical blue line indicates the interhemispheric gap.

musicians revealed generally stronger activations in M1 bilaterally, there were also extraordinary strong activations on the nondominant M1 for three of the four unimanual tasks (RF, RS, LF). The control subjects showed stronger activation in SMA proper bilaterally compared to the professional pianists for all bimanual and unimanual movement conditions except for the unimanual RS condition. In fact, SMA-proper is only slightly activated in pianists while SMA-proper is activated in nearly all conditions for the non-musicians. A much more striking difference between piano players and non-musicians emerged for the activation within pre-SMA. This area was basically not activated in piano players except for PP1, who revealed an activation on the left pre-SMA during the unimanual RS condition. NM2, however, showed substantial activations in pre-SMA for all movement conditions while NM1 revealed activations in this area during the bimanual conditions and during the unimanual conditions with the non-dominant hand.

In this study, we examined two highly professional pianists and their cortical activations in primary and secondary motor areas during the performance of relatively complex bimanual finger movements. It is clear that pianists engage in vastly more complex movements during regular play but the bimanual task preserves, in a simplified version, the essential elements of temporal integration of the two hands so important for pianists. For non-musicians, the bimanual task is quite difficult [14]. Because the professional pianists examined here practised the piano playing intensively for a long time, we suggest that they have a high level of motor skill, especially for bimanual movements. In addition, we also suggest that this increased motor skill should be associated with reorganised neural assemblies within the primary and secondary motor areas. In fact, we found substantial differences in terms of cortical activations between pianists and the control subjects, despite the fact that they did not differ substantially with respect to the measured motor performance except that they tapped slightly faster with the subdominant left hand during the RSLF condition. Non-musicians revealed stronger hemodynamic responses within the left primary (M1) motor area and bilateral in SMA proper. However, when the sub-dominant hand took the faster rate non-musicians revealed very strong activations in mesial motor areas including pre-SMA, the rostral and caudal CMA. There were also stronger activations in the right M1, LPi, and in a posterior paracentral region including the precuneus. In recent studies it has been shown that these motor areas are activated when motor control is becoming more complex and unpredictable both for unimanual and bimanual movements [3,4,10]. In addition, brain-imaging studies in humans have shown that the region presumably corresponding to the CMA is partly active when a variety of motor tasks require subjects to voluntarily select movements (for a summary see [16]). Related to our findings, one may assume that non-musicians rely more strongly on explicit and voluntarily motor control strategies while professional piano players control their movements in a more automatic fashion.

Thus, these data suggest that professional pianists use smaller neural networks within the primary and secondary motor areas in order to control bimanual movements. If this contention is correct, one might assume that the professional pianists examined here are controlling their movements much more efficiently. One reason for an increased motor control efficiency might be related to the 'degrees of freedom problem'. According to this theoretical assumption, different muscles are functionally linked together and controlled conjointly [2]. In this context it is speculated that with increasing motor skill levels more and more effectors are linked together, thus reducing the number of 'degrees of freedom' to control via motor commands [19]. In this sense, the highly trained pianists are most likely controlling lesser 'degrees of freedom' for these tasks, thus enabling them to control uni- and bimanual movements much more efficiently with smaller neural networks than non-musicians. This in turn would increase the control capacity for pianists because they now can control more 'degrees of freedom' or more motor programs with a given network. Considering that highly trained musicians also have larger hand motor areas [1] this would suggest that they have an efficiently organised neural network as well as a generally larger network in the hand motor area at their disposal.

Our data suggest that the activation of motor control areas is a function not only of task complexity but also of motor skill. Although recent brain imaging studies showed that increased complexity of motor tasks is associated with extended activations in primary and secondary motor areas [3,4,10], there are only few studies published that describe cortical activations relative to motor skill acquired by long practise. Until now there is only one other paper that also examined cortical activations of professional pianists in the context of practise [9]. Applying a simple unimanual tapping task, they also found reduced activations in secondary motor areas for the professional piano players. However, these authors found that professional musicians revealed increased M1 activation contralateral to the moving hand. Unfortunately, this effect is confounded with faster tapping speed of the musicians compared to the non-musicians, and it is difficult to disentangle whether increased movement speed or altered cortical organisation is responsible for this effect. In the present study, we found reduced activation in M1 for the professional piano players both during the bimanual conditions and during the unimanual RF conditions. In our study, speed was not a factor because subjects could set their own pace. For this reason, there was no overall differences in speed of tapping between the pianists and control subjects in the present study. Our two pianists, however, did tap faster with their subdomiant left hand, in the bimanual condition – a finding which may be a direct consequence of piano playing because piano playing strongly relies on the independent use of both hands. However, this faster tapping was not associated with increased activation in the right M1, thus suggesting that the piano players control the movement of the subdominant hand more efficiently. Interestingly, we found stronger activation within a lower part of the left central sulcus in the vicinity of the hand motor area in professional musicians. This activation may indicate a more extended network of neurons involved in hand motor control for pianists. Thus, we see two separate effects of extensive motor practis: (1) the anatomical substrate used to guide the hands is more extensive for those with higher skill and long-term practise and (2) functional activation for given movements within that larger region can activate an absolutely smaller area in the motor cortex in highly practised individuals than is the case for less skilled individuals. Long term practise, therefore, has a dual impact, providing a greater network of neurons that are involved in hand motor control, and allowing greater functional efficiency within that increased neural network.

Applying self-paced bimanual and unimanual tapping tasks to two highly professional pianists and two carefully matched control subjects, we found that the pianists exhibited reduced hemodynamic responses in the primary and secondary motor cortices as compared to the non-musician control subjects. This general lesser degree of activation in primary and secondary motor areas was independent of the motor task applied as well as independent of movement rate. Therefore, we assume that pianists use smaller neural networks in the primary and secondary motor areas to control uni- or bimanual movements, thus reflecting a more efficient neural organisation for hand motor control.

Note added in proof

During proof reading of the current paper a study has been published applying complex unimanual movements in professional pianists also finding the cortical motor areas activated to a much lesser degree in pianists [20].

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