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Research report

Playing piano in the mind—an fMRI study on music imagery and performance in pianists

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Abstract

Reading of musical notes and playing piano is a very complex motor task which requires years of practice. In addition to motor skills, rapid and effective visuomotor transformation as well as processing of the different components of music like pitch, rhythm and musical texture are involved. The aim of the present study was the investigation of the cortical network which mediates music performance compared to music imagery in 12 music academy students playing the right hand part of a Bartok piece using functional magnetic resonance imaging (fMRI). In both conditions, fMRI activations of a bilateral frontoparietal network comprising the premotor areas, the precuneus and the medial part of Brodmann Area 40 were found. During music performance but not during imagery the contralateral primary motor cortex and posterior parietal cortex (PPC) bilaterally was active. This reflects the role of primary motor cortex for motor execution but not imagery and the higher visuomotor integration requirements during music performance compared to simulation. The notion that the same areas are involved in visuomotor transformation/motor planning and music processing emphasizes the multimodal properties of cortical areas involved in music and motor imagery in musicians.

Theme: Neural basis of behavior,
Topic: Cognition

Keywords: fMRI; Music performance; Music imagery; Visuomotor integration

1. Introduction

Playing a music instrument is among the most complex of motor tasks [20]. The player has to integrate high-speed sequential hand movements into a rhythmic and expressive context. An additional requirement of music performance is notereading. Notereading comprises the translation from the visual spatial domain to a representation which provides the information for a program specifying the patterning, timing and positioning of finger movements [32].

The use of functional imaging has allowed insights into the processing of music processing in the brain. Musical performance has been investigated by a number of studies concerning the programming of motor action, the generation of rhythm and the integration of the musical syntax into an individual interpretation of music [15,17,20,29,33]. The programming of movements predominantly involves the supplementary motor (SMA) and premotor areas [5,31], whereas rhythmic patterns are generated by a frontoparietal network [27]. In professional piano players, there are learning-related changes in cerebral motor representation; thus it was found that professional piano players show less cerebral activation in premotor and motor areas when compared to non-musicians performing the same movement [9,14].

It is known that professional musicians not only rehearse their musical skills by daily practice, but use additional strategies of mental imagery of music performance. For example, Horowitz practiced mentally before playing in concerts in order to avoid the feedback of a piano other than his own. Rubinstein did so in order to efficiate daily practice [30].

The neural correlate of mental rehearsal and music performance in pianists which underwent a yearlong training of the combination of motor skills and music processing

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is, so far, not well understood. The main component of mental rehearsal is motor imagery. Motor imagery denotes a mental simulation of action which involves most of those parts of the visuomotor system which are active during execution. It provides a possibility for the central nervous system to evaluate the consequences of future actions and to shape the motor system in preparation of the actual execution of action [11]. There are some interesting aspects of simulated action which reveal the close relationship between motor imagery and motor action: for example, the timing patterns of both processes are similar [36] and the changes in corticospinal excitability involve the same muscles in both conditions [2]. Functional imaging studies have investigated different modalities of motor imagery compared to performance in non-musicians. It was found that imaging and performance activate essentially the same cortical regions [4,16,22], with the exception, however, of the primary motor cortex; the results regarding the involvement of the primary motor cortex in motor imagery differ across studies.

Previous studies in non-musicians have established the use of the comparison of motor performance and motor imagery to investigate the planning processes of visuomotor integration within the cortical network. The present study investigated the cerebral network which is active during piano performance and imagery of piano performance in students of piano playing of a music academy in order to investigate cerebral regions mediating notereading and playing an instrument. Investigation of music students provides insights into the cerebral organisation of a highly trained cortical network processing music and motor planning. However, unlike previous studies on motor learning in non-musicians, we focused on performance and imagery of music; therefore, trained music students were studied solely.

2. Materials and methods

2.1. Subjects

Twelve students (mean age 26.6 years), 10 female, 2 male, of the Cologne School of Music were investigated. All subjects were right-handed according to the Edinburgh handedness inventory. All students had piano as their principal instrument. The average time since the beginning of piano practice was 18.4 years and the average time of weekly practice with the piano was 22 h. Musical training had on average started at the age of 8 years. Written informed consent was obtained from all subjects in accordance with the guidelines of the local ethical committee.

2.2. Task

In order to compare the activation patterns which occur during right-handed piano playing in the ipsilateral and contralateral hemisphere we looked for a piece of music to which the piano player did not use automatically associated left hand movements. Therefore, the piece of music, which the subjects had to perform, was taken from Bela Bartok's collection of short piano pieces called Mikrokosmos. A piece of 30 bars entitled Triolak was chosen. The subjects were shown only the notes for the right hand of this piece on a computer screen. They had to play this piece with the right hand on a keyboard. This keyboard was a commercially available electronic keyboard synthesizer which was stripped of all electronic components to make it suitable for MRI. Playing the keyboard did not, therefore, elicit any sound. Before MRI scanning, the subject had to play the piece until they were familiar with it. In the MRI scanner the subjects lay in a prone position with the keyboard placed on their lap. The notes of the music piece were presented via a mirror placed in front of the subjects head. As control, the note "a" was presented as crotchet in musical notation as many times as the total number of notes in the Bartok piece. The subjects were instructed to read the notes of the control condition similarly to the music piece, but not to play it.

There were two experimental conditions during "on"-periods of an epoch paradigm, alternated by the baseline condition ("off"-periods). In the music performance condition, the subjects had to play the presented piano piece with their right hand on the keyboard. In the music imagery condition, the subjects were instructed to read the notes and imagine themselves playing the piano piece presented on the screen. The performance of the piano piece and the lack of hand movement during music imagery or the "off"-periods was controlled by monitoring the hand movements of the subjects with an extra videocamera within the scanner room focused on the hands during the functional magnetic resonance imaging (fMRI) session.

Table 1
Localizations and *t*-values of the fMRI activations found for music performance minus baseline

Music performance	BA	Coordinates			*t*-value
Region		*x*	*y*	*z*	
Left sensorimotor	2	−53	−27	35	10.62
	3	−39	−26	54	14.55
	4	−50	−9	47	7.97
	6	−12	−9	53	7.80
Right sensorimotor	6	42	0	53	8.63
Right frontal	9	53	7	33	7.60
	32	12	11	46	6.12
Left superior parietal	5	−33	−41	57	12.47
	7	−24	−52	−58	7.98
Left inferior parietal	40	−39	−35	54	15.65
Right superior parietal	7	21	−61	56	10.29
Right inferior parietal	40	45	−30	43	6.47
Left occipital	37	−50	−62	−7	7.21
Right cerebellum		3	−56	−17	9.49
Left cerebellum		−24	−59	−20	6.32
Left thalamus		−15	−20	−4	8.36

The coordinates given refer to the Talairach space.

After the fMRI-session, the subjects were asked to complete a questionnaire regarding their sensations during the experimental conditions. In addition, they had to rate the difficulty of the piano piece and to fill out the "Vividness of Mental Imagery Questionnaire" [8]. This questionnaire has a rating scale from 1 to 5 for the vividness of one's imagery with 1 as the most vivid level.

2.3. FMRI procedure

The cerebral activation was studied with functional magnetic resonance imaging employing the blood oxygen level-dependent contrast on a 1.5T. Philips Gyroscan (Philips Best, The Netherlands) scanner in a standard headcoil. An epoch design was used with three active conditions (music imagery) and three control conditions (reading of the note "a"). The fMRI sessions comprised four Dummy scans followed by 72 whole-brain scans using single-shot gradient-refocused echo-planar imaging (EPI) (TR = 3.587 s, TE = 50 ms, flip angle = 90°, slice thickness = 5 mm, 22 slices). Thus the duration of each epoch was 43 s.

2.4. Data analysis

The fMRI Data were analysed using Statistical Parametric Mapping software (SPM99, http://www.fil.ion.ac.uk/spm, London, UK). The dummy scans were discarded. The remaining scans were realigned and spatially normalized to the standard stereotactic space using the EPI-template of the Montreal Neurological Institute (MNI). The voxel size was 3 × 3 × 3 mm. Subsequently the normalized data were smoothed using a Gaussian kernel = 9 × 9 × 9 mm in order to improve the signal-to-noise ratio. For the following parameter estimation, an appropriate design ma-

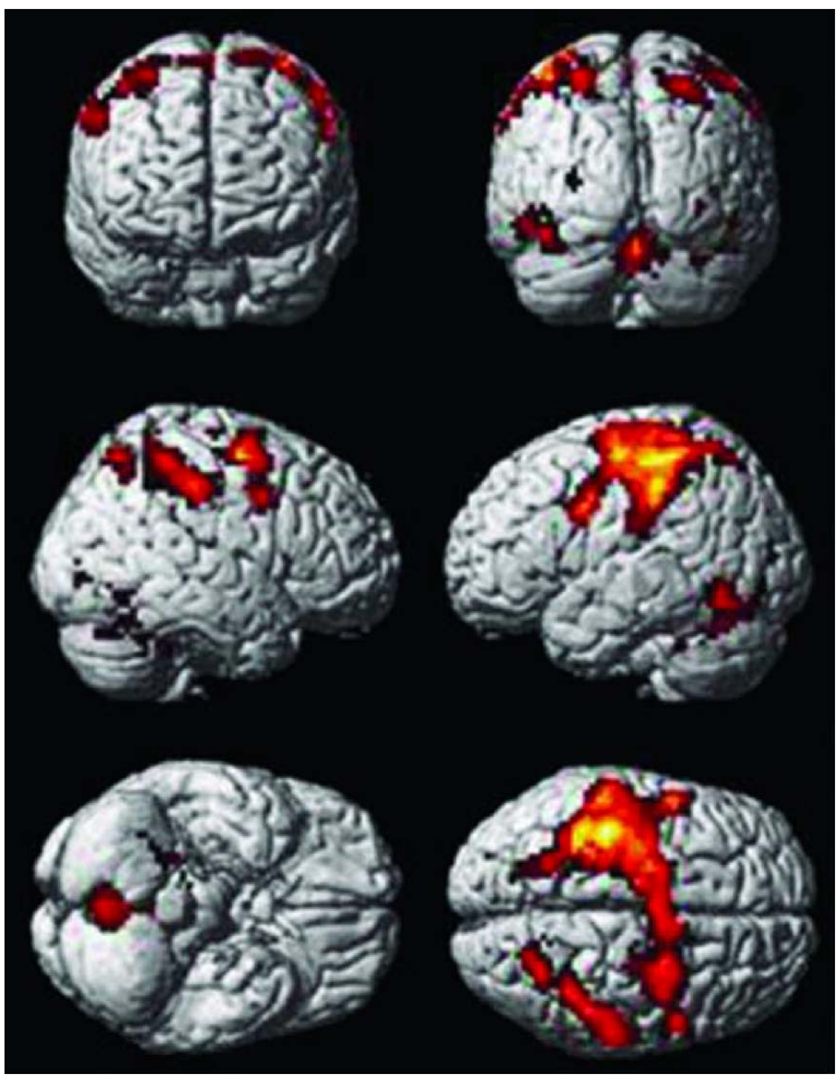

Fig. 1. The cortical activations found for music performance minus baseline ($p < 0.05$, corrected within 30 × 30 × 30 mm around coordinates found in a pilot study). The activations comprise the primary sensorimotor cortex in the left hemisphere and the premotor cortex and the cerebellum bilaterally, in addition to a parietal network of precuneus and BA 40.

trix was specified using a box-car function as reference waveform. The voxel-by-voxel parameter estimation for the smoothed data was carried out according to the general linear model. In order to test hypotheses about regionally specific effects, the resulting estimated beta-maps were compared by means of linear contrasts of each active and control condition or of the comparison of two active conditions. A map of *t*-statistic values (SPM(*t*)-map) was obtained from this analysis. To take interindividual variations into account, a random effect model was applied [3] comparing the raw data of the subjects with a one-sample *t*-test ($p = 0.001$). The resulting activations were corrected within boxes of 30 × 30 × 30 mm around voxels found to be active in a pilot study (part of the data was published in Krings et al. [14]). In this study, the ROI were defined on the anatomical images as follows:

1. M1 with its putative hand representation area, defined by the omega-shaped knob of the central sulcus.
2. SMA, defined as the mesial part of Brodmann area 6 with the caudal border formed by the depth of the cingulate sulcus.
3. Superior parietal area defined as the region posterior to the postcentral sulcus and superior to M1.
4. Premotor area defined by the precentral and arcuate sulcus lateral to SMA.

In addition to these areas, we included in the present study the occipital region centered at the sulcus calcarinus. The resulting SPM(*t*)-maps were transformed into Talairach space [38].

3. Results

3.1. Behavioral data

Analysis of the videotapes recorded during the fMRI session revealed that all subjects performed the music piece correctly and did not move their hands during the "off"-periods or the music imagery periods of the epoch paradigm.

All but one subject reported hearing tones of the music piece in their "inner ear" during both experimental conditions. None of the subjects reported to have imagined music during the "off-periods". Furthermore, the subjects were asked to rate the difficulty of the piano piece on a scale from 1 to 5 arbitrary units with 5 as most difficult level. All subjects rated the piece with level 1 or 2 (average 1.42 arbitrary units). The analysis of the Vividness of Movement Imagery Questionnaire (VMIQ) showed an average level of 2.01 for the whole questionnaire for imagery of self-generated movements and of 1.99 for the subset which tests imagery of precise movements which corresponds to a "clear and reasonably vivid" imagery.

Table 2
Localizations and *t*-values of the fMRI activations found for music imagery minus baseline

Music imagery	BA	Coordinates			*t*-value
Region		*x*	*y*	*z*	
Left sensorimotor	6	48	2	36	7.65
Left frontal	9	−50	5	33	7.73
Right sensorimotor	6	48	5	47	6.12
Left superior parietal	7	−27	−56	53	8.45
Left inferior parietal	40	−42	−33	38	6.75
Right superior parietal	7	24	−61	56	8.22
Right inferior parietal	40	53	−30	37	5.82
Left occipital	18	−24	−88	−6	8.87
	19	−33	−87	−7	10.17
Right occipital	18	30	−84	2	7.62
	19	39	−79	−4	5.33
Left cerebellum		−24	−65	−24	6.70

The coordinates given refer to the Talairach space.

3.2. fMRI data

In the analysis of the fMRI data, a predominantly frontoparietal cortical network was found to be active during piano performance. This network included the primary sensorimotor cortex in the left hemisphere and the premotor cortex bilaterally. In the parietal cortex, secondary sensory areas in the left hemisphere were activated. In addition, a bilateral activation of the precuneus (BA 7) and the medial part of BA 40 was observed. There was a small activated cluster in the left occipital region (BA 37). Furthermore, there was bilateral activation of cerebellar areas, with a large cluster in the right hemisphere, and of the left thalamus (Table 1, Fig. 1).

The activations found in the imagery condition corresponded to those in the music performance condition with the exception of the primary sensorimotor area of the left hemisphere and the right cerebellum, which were not active. In general, the activations found for imagery were smaller than for performance. In the imagery condition, an additional bilateral activation in the extrastriate cortex was revealed (Table 2, Fig. 2).

The comparison of music performance vs. imagery revealed the primary sensorimotor cortex of the left hemisphere, part of the bilateral parietal activations and cerebellar regions (Table 3, Figs. 3 and 4).

4. Discussion

To what extent do the fMRI activations found in the present study mirror the different cognitive requirements of music performance and imagery? First, the visuospatial and motor aspects of notereading and the transformation of this information into complex hand movements are addressed. In the second part, the possible role of the different areas in the cortical processing of music is discussed.

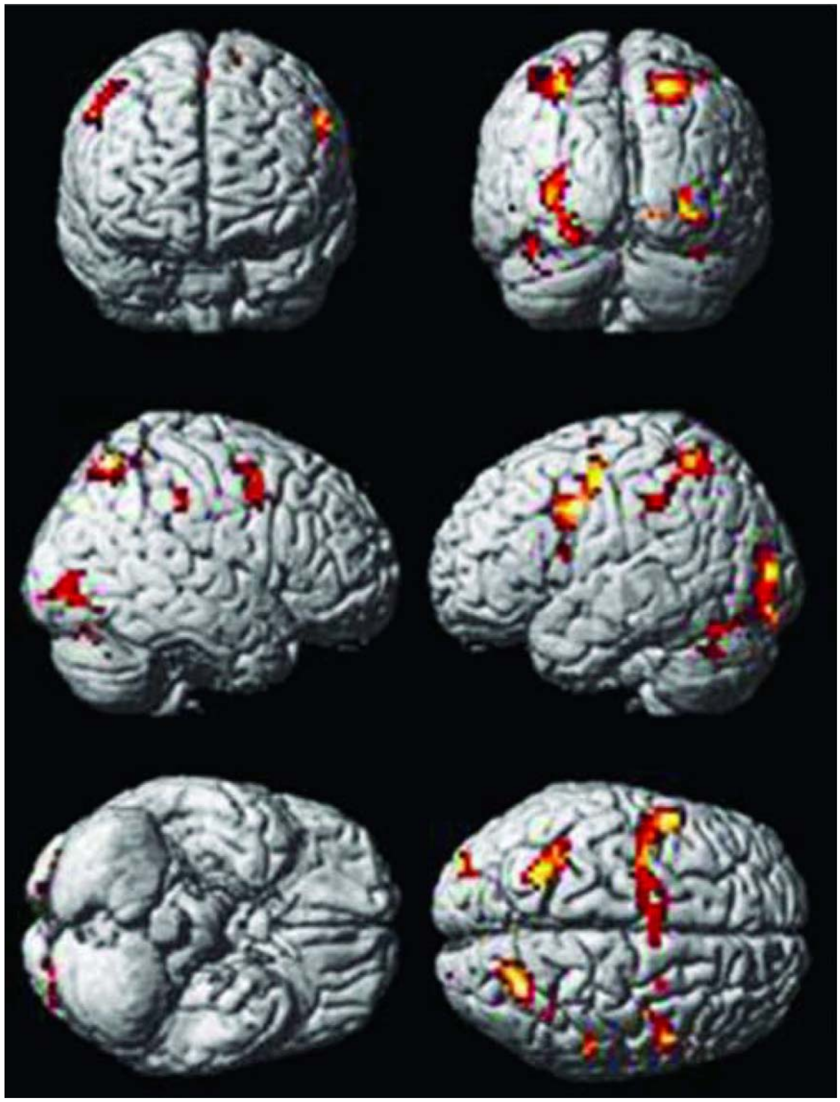

Fig. 2. The cortical activations found for music imagery minus baseline ($p < 0.05$, corrected within $30 \times 30 \times 30$ mm around coordinates found in a pilot study). With the exception of the left primary sensorimotor area and the ipsilateral cerebellum, the activated network is essentially the same as in the music performance task. This emphasizes the function of the bilateral fronto-parietal network, together with the occipital cortex in the planning of visuomotor transformation and musical processing. fMRI activations are projected on a segmented SPM-template.

4.1. The fronto-parietal network

When pianists played music on a silent keyboard, they activated a network comprising the left primary sensorimotor area, the right cerebellum and the premotor/supplementary motor areas, the precuneus together with the intraparietal sulci (Brodmanns area 40) and the bilateral extrastriate visual areas BA 18 and BA 19. In the left hemisphere, an additional activation was found in the posterior part of the dorsolateral prefrontal cortex (BA9). Imagery of music performance activated the same network with the exception of the primary sensorimotor area in the left hemisphere and the right cerebellum. This difference between the two experimental conditions is in accordance with prior studies which have investigated the execution and imagery of motor tasks in non-musicians [4,16,22]. The activation of frontal and parietal areas corresponds to the results of studies on motor imagery and motor performance. In our study, in accordance with a task which required action or imagery of movements of the right hand only, supplementary and premotor areas were activated predominantly in the left hemisphere. This is in agreement with activation patterns found for the execution of complex movements in pianists [9,14]. The finding that great overlap exists between activations found for motor execution and motor imagery is well established [11,12].

There are, however, differences between the two conditions regarding the extent of activation of the frontoparietal network: during music performance, there was additional activation of the primary sensorimotor cortex. Furthermore, ipsilateral premotor activity was more pronounced during performance. These differences between

Table 3
Localizations and *t*-values of the fMRI activations found for music performance minus music imagery and vice versa

Region	BA	Coordinates			*t*-value
		x	*y*	*z*	
Performance vs. imagery					
Left sensorimotor	4	−27	−27	51	6.73
	6	−12	−12	50	6.30
	2	−50	−24	48	7.27
	3	−36	−27	51	8.16
Left inferior parietal	40	−33	−38	57	9.57
Right inferior parietal	40	36	−38	57	6.37
Right cerebellum		9	−48	−23	11.59
Left cerebellum		−18	−71	−14	6.78
Imagery vs. performance					
Left occipital	19	−3	−92	24	6.34

The coordinates given refer to the Talairach space.

imagery and execution of a piano piece correspond well with previous results on the cortical representation of imagined and actual movements. A study, which compared activated pixels during motor execution and motor imagery qualitatively and quantitatively [22], found a great overlap between the regions involved in motor performance and motor imagery. However, the signal changes found in the imagery task were smaller than in the motor performance task, consistent with the concept of a subliminal activation of the motor system in motor imagery. A further study has supported the view that there is a considerable anatomical overlap between execution and imagery of motor tasks, especially in the dorsal Brodmann area 6 and in the SMA [16].

The parietal fMRI activations showed an interesting difference regarding the involvement during imagery and performance of music: whereas the precunei were activated to the same extent during both tasks, the region around the intraparietal sulci (BA 40), part of the posterior parietal cortex, exhibited a significantly stronger fMRI activation during music performance compared to imagery. Recent studies [25,26] have identified the precuneus and the intraparietal sulcus as regions whose activity correlates positively with learning of specific reactions to visual stimuli. The pattern of activation for the two regions was, however, different in these experiments. The precuneus was involved preferentially in processes of acquisition and retrieval of reaction sequences in the working memory. It is part of the superior parietal lobe which mainly processes sensorimotor integration [10]. In contrast, the IPS is thought to mediate eye–hand coordination. A recent study mapping the fMRI activity of the parietal cortex during different cognitive tasks found that IPS is primarily involved in visuospatial processing [34]. In addition, it would appear that the posterior parietal cortex (PPC), and perhaps more markedly the left PPC, may be the cerebral region where motor images are stored [37,39]. It is part of the inferior parietal lobe which processes the coordination of body movements within space [10,34]. A recent study investigated sight-reading in musicians revealed the IPS as critical structure for notereading [29]. The authors argue that this region may mediate the specific visuomotor transformation of notes into complex movements due to years of musical practice. Taken together, there is strong evidence from previous studies that the posterior parietal cortex mainly mediates visuomotor transformation whereas the precuneus is involved in working memory processes. The stronger fMRI activation during music performance compared to imagery within PPC therefore reflects a greater level of visuomotor integration required during motor execution compared to mental simulation.

4.2. Cerebellar and occipital activations

The cerebellum was also found to be active during both tasks. This is in accordance with the results of studies of overt task performance [9,14]. In an investigation of cerebral correlates of motor imagery, involvement of the cerebellum was found to be crucial [16]. Further tasks in which cerebellar activity has been shown are motor/rhythm timing [31] and coordination [23]. Thus it is likely that the cerebellar activation seen in our task can be assigned to the frontoparietal network responsible for coordination and visuomotor integration.

In addition to the frontoparietal network, this study has demonstrated a consistent bilateral activation of extrastriate areas (BA 18 and 19) during imagery of music performance. Music performance led to activation in the anterior part of the occipital cortex (BA 37) of the left hemisphere. This may be due to the higher visual complexity of the experimental conditions which required notereading of the notation of a piano piece compared to the control condition which involved repetitive reading of the same note. A previous study on music performance [33], which compared reading of a musical score with the presentation of simple dots, found a similar activation. Furthermore, the occipital activation during the imagery task may represent an additional visual imagery component in the experimental conditions. Visual imagery has been shown to involve extrastriate areas [13]. Sirigu and Duhamel [35] found that in imagery tasks involving spatial manipulations visual and motor imagery show complementary activity. Music performance requires the transformation of visual information into complex movements and may, therefore, include components of both visual and motor imagery.

4.3. Components of music processing

There are hints from several studies that musical performance and imagery is processed both in the frontoparietal and in the occipital network [17,28], both of which were found to be active in this study. A recent study investigating the dynamics of brain activation in pianists during music perception has shown that there is an activation of the

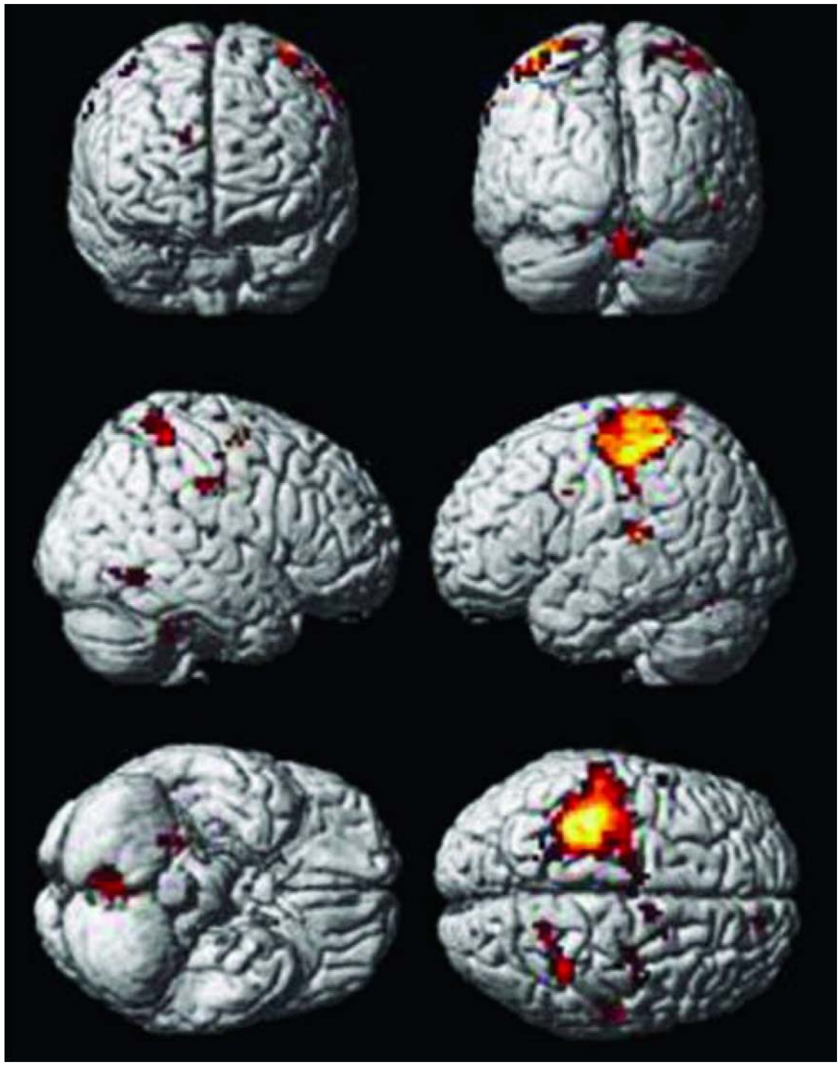

Fig. 3. The cortical activations found for music performance minus music imagery ($p < 0.05$, corrected within $30 \times 30 \times 30$ mm around coordinates found in a pilot study). The main activation is the contralateral primary sensorimotor cortex, which is more active during execution than in imagery, in line with previous findings. In addition, part of the posterior parietal cortex bilaterally shows stronger activation during motor execution compared to imagery. fMRI activations are projected on a segmented SPM-template.

cortical motor areas when listening to music [7]. This has been seen as evidence for the close relationship between perception and performance of music in musicians.

The activation of the premotor areas is a common finding of studies involving musical imagery [6,24]. Interestingly, in these studies the activation of the premotor area was related to the generation of musical images and was not seen when retrieval of melodies was required. This result has been interpreted as a "singing to oneself strategy" in auditory imagery tasks, a subvocal singing process that highlights the close relationship between generation of auditory and motor images. Another of our findings corresponds to previous findings: as the subjects reported to hear music before their inner ear, one might expect that our paradigm would evoke activity in the superior temporal gyri. This was not, however, the case. Halpern and Zatorre [6] have shown that these areas are only involved when images of familiar melodies but not when unknown melodies are generated. This is supported by a recent study on covert music rehearsal [15] which compared imagined musical performance with fingertapping and passive music listening. In this study, to our knowledge so far the only fMRI investigation of covert music rehearsal, a broad frontoparietal network was found to be active during imagery of music performance which is in line with our results.

Results from several studies highlight the possible role of the parietal areas for music processing. A study investigating auditory imagery of single tones found activity in the precunei in addition to the premotor areas [40]. Results on music–brain interaction have suggested that music processing and visual imagery are closely connected and that the precuneus plays a key role in this process [18].

A component of musical structure that is highly associated with the frontoparietal network and cerebellar areas

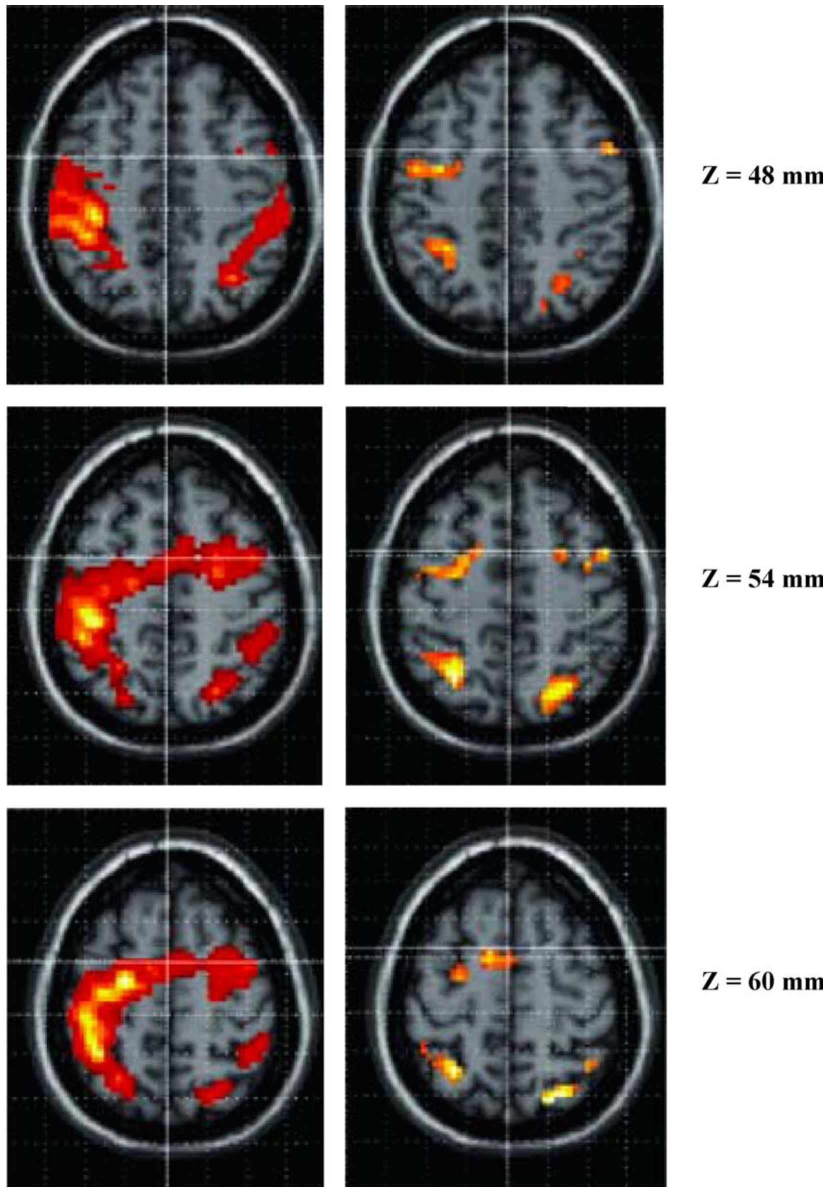

Fig. 4. A comparison of the frontal and parietal activation in music performance (left) and music imagery (right) in three Z-levels of the Talairach space. Whereas the primary motor cortex is activated almost exclusively in music performance, the more anterior frontal and the parietal areas are active during both conditions.

found to be active in this study is rhythm processing [27]. The intraparietal sulcus in particular, which was activated both during music imagery and music performance in this study, would seem to mediate the cortical representation of rhythm: a recent investigation of time perception in different modalities [31] found that the IPS is crucially involved in rhythm monitoring at the perceptual level, irrespective of the modality of presentation. Sakai et al. [27] have shown that the IPS is also involved in rhythm learning irrespective of its interval. Thus part of the frontoparietal network activated in the present study also seems to be involved in rhythm processing. These areas may mediate, therefore, not only visuomotor integration and coordination during music performance, but also rhythm processing.

The only cortical activation with a clear lateralisation in the present study was found in the left posterior part of the dorsolateral prefrontal cortex (BA 9). Ohnishi et al. [19] compared music perception in musicians and non-musicians and found that activation in this region was significantly higher in musicians. Musical training may therefore lead to an involvement of the DLPFC in musical processing strategies.

The occipital network found in this study would also seem to be involved in musical processing. In the study by Halpern and Zatorre, activation of the right BA 19 was found for auditory image generation. This is supported by an investigation of music perception that sought to disentangle the different aspects of music [21]. The authors found the left precuneus and cuneus (BA 18/19) were the main areas active in a pitch discrimination task. This was seen as a mental imagery strategy for processing this musical component.

Taken together, all the areas found to be active in our study may be related to music processing. We suggest that the frontoparietal network and the cerebellum are involved slightly more in rhythm processing, whereas the precuneus and the occipital regions seem to play a role in the processing of pitch. The notion that the same areas are involved in visuomotor transformation/motor planning and music processing emphasizes the multimodal properties of cortical areas involved in music and motor imagery in musicians.

One potential bias of the study is the fact that more female than male subjects were investigated. It is not clearly understood if gender differences might lead to differences in cerebral activation patterns during cognitive tasks. In a recent study employing verbal fluency and visuospatial cognitive tasks, the differing levels of blood estrogen were a main determinant of global activation significance levels whereas the localization and the hemispheric dominance did not show any differences between male and female subjects [1]. However, it is not clear whether this holds true also for music performance and imagery.

In conclusion, investigation of the cerebral network which is active during execution and imagery of music performance in pianists reveals a frontoparietal network that is well described as network subserving motor imagery and visuomotor association, and an occipital network most likely to be concerned with notereading. These areas work together during imagery and execution of musical performance. However, music performance compared to imagery leads to a significantly greater fMRI activation not only of the primary sensorimotor cortices but also of the posterior parietal areas bilaterally whereas the precunei showed no differential activation. This reflects the higher level of visuomotor integration required during motor execution. The different components of music, such as generation of rhythms, pitch discrimination, or generation of auditory images when reading notes, are possibly processed within the whole activated network.

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