Partially Overlapping Neural Networks for Real and Imagined Hand Movements

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Neuroimagery findings have shown similar cerebral networks associated with imagination and execution of a movement. On the other hand, neuropsychological studies of parietal-lesioned patients suggest that these networks may be at least partly distinct. In the present study, normal subjects were asked to either imagine or execute auditory-cued hand movements. Compared with rest, imagination and execution showed overlapping networks, including bilateral premotor and parietal areas, basal ganglia and cerebellum. However, direct comparison between the two experimental conditions showed that specific cortico-subcortical areas were more engaged in mental simulation, including bilateral premotor, prefrontal, supplementary motor and left posterior parietal areas, and the caudate nuclei. These results suggest that a specific neuronal substrate is involved in the processing of hand motor representations.

Introduction

Motor imagery can be defined as the ability to go 'through the motions' in one's mind and can be used to investigate the representational aspects of movement. Several psychological studies in normal subjects using mental chronometry tasks have shown that there is a remarkable parallelism between motor imagery and motor execution. First, the time to mentally complete a particular movement is similar to the time needed to execute the corresponding motor act (Decety and Michel, 1989; Jeannerod, 1994; Crammond, 1997; Jeannerod and Frak, 1999). Second, vegetative responses (such as increasing heart rate and blood pressure) associated with physical effort vary in the same manner during both motor imagery and motor performance (Decety et al., 1991). Third, mental motor images are constrained by the same physical laws (such as speed–accuracy trade-off as stated in Fitt's law) that apply to movement execution (Sirigu et al., 1995a, 1996).

Studies using positron emission tomography (PET) and functional magnetic resonance imaging (fMRI) techniques demonstrated that most of the regions that are active during overt movement execution, such as the parietal and premotor cortex, the basal ganglia, and the cerebellum, are active as well during mental simulation (Decety et al., 1994; Stephan et al., 1995; Grafton et al., 1996a). One important corollary of this idea is that movement imagination and execution share many properties, including a common neuronal circuitry (Jeannerod, 1994, 1999; Jeannerod and Frak, 1999). Accordingly, we should expect that a lesion anywhere in the motor circuitry would lead to a parallel deficit for the executed and imagined movement. Indeed, it has been shown that patients with right motor cortex damage (Sirigu et al., 1995a) and patients with basal ganglia dysfunction following Parkinson's disease (Dominey et al., 1995) show a parallel impairment in imagined and executed movements. This suggests that the output produced in the motor and striatal pathways during motor imagery is similar to what is occurring during movement execution. Recently, however, Sirigu et al. demonstrated that patients with parietal lesions lose the ability to predict the duration of a movement through mental rehearsal, contrary to normal subjects and patients with motor cortex damage (Sirigu et al., 1996). Moreover, patients with left parietal lesion were impaired when imagining movements of both the left and the right hand, while patients with right parietal lesion only showed an imagination deficit of the contralateral hand.

Thus, while the motor cortex and the basal ganglia do not appear critical in forming or maintaining a mental image of a limb in action, the parietal cortex, and perhaps predominantly the left parietal cortex, could be the cortical area where motor images are stored. Sirigu et al. (Sirigu et al., 1996) suggested that the parietal cortex sets up an internal model of the projected movement, and allows us to make predictions about how the movement will unfold and about its expected outcome. Following this hypothesis, we expect that imagined movements activate specific areas within the parietal cortex that are partially distinct from those involved in movement execution.

A role for the posterior parietal cortex in motor imagery has been suggested by other neuroimagery studies using tasks such as complex motor procedures (Roland et al., 1980), joystick (Stephan et al., 1995) or grasping movements (Decety et al., 1994; Grafton et al., 1996a), and generation of a visual image of finger movements (Deiber et al., 1998). However, none of these studies reported a functional specificity of parietal areas during movement imagery.

In the present study, we compared motor imagery with motor execution of hand movements. We were interested in knowing whether a specific cerebral network is involved in the mental simulation of hand movements as compared with their execution. Following the results of Sirigu et al. (Sirigu et al., 1996), we expected to find areas within the parietal cortex specifically devoted to mental movement rehearsal and a strong and predominant activation of the left posterior parietal cortex during movement imagination of both hands.

Materials and Methods

Subjects

We studied eight right-handed healthy volunteers (five males and three females, mean age 26.6 years, range 21–35 years) at 3 T using a Bruker Whole-body Magnetic Resonance Imaging system. Subjects had no history of neurological or psychiatric disease, they were paid for their participation and gave informed consent. The experiment was approved by the local ethics committee. All subjects completed the Edinburgh Handedness Inventory and were strongly right-handed (Dellatolas et al., 1988).

Subjects were required to perform one of the following tasks: execution of hand movements, imagination of the same hand movements and rest.

Movement Execution
Subjects were required to execute a simple (simultaneous flexion/extension of the fingers) or complex (selective flexion/extension of the index and the little finger) continuous movement, as previously described (Sirigu *et al.*, 1996).

Movement Imagination
Subjects were asked to imagine the same movements without actually performing them. EMG was recorded from surface electrodes positioned on the forearm, during rest, imagination and execution of the same simple and complex movements. Surface EMG did not detect any muscular activity during imagination and rest conditions, whereas a regular pattern of muscular activity during execution of hand movements (200–600 mV signals) was detected. The ability of each subject to perform mental imagery was assessed by means of a modified version of a motor imagery questionnaire (Hall et Pongrac). Imagery scores ranged from eight (good imager) to 56 (poor imager). Subjects were considered as having good imagery abilities when their score fell between eight and 32, and those with poor imagery abilities between 33 and 56. All subjects showed good imagery abilities (mean 16.0 ± 5.4, range 10–22 for visual imagery and mean 17.9 ± 7.2, range 9–26 for kinesthetic imagery). This questionnaire also provided the subjects with an opportunity to train themselves to the motor imagery task.

Both imagined and executed movements were externally paced at 0.5 Hz by an auditory stimulus.

Rest
Subjects were asked to stay motionless and relax. The same auditory tone was heard at the same rate as in the two other conditions.

Experimental Design
There were five different conditions: rest (R), simple imagined (SI), simple executed (SE), complex imagined (CI) and complex executed (CE). A resting period alternated with each of these experimental conditions which were randomized across eight runs. Four runs were performed with the right hand and four runs with the left hand. Each run was composed of 12 epochs, each lasting 20 s. At the beginning of each epoch an auditory sentence warned the subject of the type of task to perform in the following trials (e.g. 'simple executed'). The advantage of this experimental design over previous studies of motor imagery is that it allowed us to perform direct comparisons both between each experimental task and with respect to the rest condition.

Functional Imaging
Twenty-four 5-mm-thick axial slices were obtained with a T2* weighted gradient echo, echo planar imaging sequence, using blood oxygen level-dependent contrast (repetition time 5000 ms, echo time 40 ms, flip angle of 90°, matrix 64×64, field of view 220×220 mm^2). Fifty-two brain volumes were acquired for each run (four volumes for each of 13 epochs). The first four volumes of each run were discarded to reach signal equilibrium. Subsequently to the functional protocol, high-resolution three-dimensional anatomical images of the whole brain were also acquired (gradient-echo inversion recovery, repetition time 1600 ms, echo time 5 ms, matrix 256×256, field of view 220×220 mm^2).

Statistical Analysis
All data were performed with Statistical Parametric Mapping (SPM 96, Wellcome Department of Cognitive Neurology, London, UK). For each subject, anatomical images were transformed stereotactically to Talairach coordinates using the standard template of the Montreal Neurological Institute. The functional scans, corrected for subject motion, were then normalized using the same transformation and smoothed with a Gaussian spatial filter to a final smoothness of 5 mm. Data were analyzed on an individual (subject per subject) basis and across subjects (group analysis) using across subjects variance (random effect analysis) (Friston *et al.*, 1999). For individual analysis, data from each run were modeled using the general linear model with separate functions modeling the hemodynamic response to each experimental epoch, leaving 211 degrees of freedom per subject analyses. Covariates were used to model long-term signal variations (temporal cut-off 240 s) and overall differences between runs. Six contrasts were defined as follows: (i) execution of hand movements compared with rest; (ii) imagination of hand movements compared with rest; (iii) execution compared with imagination of hand movements; (iv) imagination compared with execution of hand movements; (v) complex compared with simple movements; and (vi) simple compared with complex movements. The absence of interaction between the imagined/executed factor and complex/simple factor was also assessed. As left and right movements were performed in separate runs, which does not allow for the differentiation of the inter-run from the left–right effects, the left versus right comparison were not assessed. Data for each hand were pooled for statistical comparisons. Statistical parametric maps were calculated for each contrast. We first thresholded the Z maps at $Z = 3.09$ ($P < 0.001$). In these thresholded maps, activated clusters were considered significant if their spatial extent was >18 voxels (or 172 mm^3), corresponding to a risk of error (type I error) of $P < 0.05$. For group analysis, parametric maps were constructed using the same threshold and the same contrasts as for the subject per subject analysis. For the basal ganglia study, a more liberal statistical threshold ($P < 0.01$) uncorrected for multiple comparison was used because for these structures multiple comparison correction for the entire volume of the brain would lead to a much too high risk of type II error (the risk of accepting the null hypothesis when it should be rejected). For small structures, such as the putamen, the thalamus and the caudate nucleus, this threshold is valid because the statistical analysis is guided by a very strong anatomical hypothesis, with well-defined and invariant anatomical landmarks across subjects.

Results

Group Results

Execution of Movement Compared with Rest
Significant signal changes were found in the primary sensori-motor, the medial and lateral premotor areas, the superior and inferior parietal areas, the basal ganglia, the thalamus and the cerebellar hemispheres bilaterally (Table 1 and Figure 1).

In the premotor cortex (PM), activation was located in the lateral [Brodmann area (BA) 6] and medial surfaces of the cortex (supplementary motor area = SMA). Activation was found in both the anterior (pre-SMA) and posterior (post-SMA) parts of the SMA, the division being marked by the vertical line (VCA line) passing at the level of the anterior commissure (AC), perpendicular to the line connecting the anterior and posterior commissures. Activation was also found in the right inferior frontal area corresponding to BA 44.

In the parietal lobe, activation was located in the primary sensory areas (SI), which correspond to BA 1–3, and in the parietal operculum (SII), which corresponds to the opercular part of BA 40 and 43. Activation was also found in the rostral part of the superior parietal regions bilaterally (BA 7) and in the left postero-inferior parietal area (BA 40).

In the basal ganglia, the putamen was arbitrarily divided into an anterior and a posterior area using the VCA line as a landmark. Activation was observed in both the anterior and posterior parts of the putamen, bilaterally. Bilateral activation was also found in the ventrolateral nucleus of thalamus and in the rostral part of the cerebellar cortex.

Imagination of Movement Compared with Rest
When imagination was directly compared with rest (Table 1 and Figure 1), activation included bilateral medial and lateral PM areas, superior and inferior parietal areas and basal ganglia.

When contrasted with the execution condition, no activation

Table 1

Coordinates of significant cluster maxima in the group analysis for imagined and executed movement versus rest comparisons

Anatomic Areas (Brodmann area)	Hemisphere	Executed movement with rest compared				Imagined movement with rest compared			
		X	Y	Z	Z-score	X	Y	Z	Z-score
Prefrontal cortex									
Dorsolateral prefrontal area (9,46)	R								
	L					−54	42	15	3,76
Rostral prefrontal area (10,11)	R					30	51	24	4,58
	L								
Inferior frontal area (44,45)	R	57	18	24	5,62	48	24	6	4,75
	L					−54	12	12	4,31
Motor and premotor cortex									
Primary motor area (4)	R	39	−15	63	7,14				
	L	−42	−18	66	6,55				
Lateral premotor area (6)	R	42	−3	60	5,67	42	6	57	5,69
	L	−36	−3	66	5,19	−42	3	51	5,35
Medial premotor area (6)									
Pre-SMA	R	6	6	57	5,11	3	6	69	6,29
	L	−9	9	51	4,37	−3	6	69	5,81
Post-SMA	R	3	−3	66	4,59				
	L	−3	−3	66	6,01	−6	−3	69	4,61
Parietal area									
Primary sensory area (1,2,3)	R	42	−33	60	5,03	54	−21	39	4,3
	L	−48	−24	57	4,94	−60	−21	39	5,18
Superior parietal area (7)	R	36	−36	66	4	24	−54	51	3,6
	L	−30	−42	66	3,66	−27	−60	54	4,63
Inferior parietal area (40)	R					36	−30	42	4,53
	L	−45	−36	60	4,95	−36	−42	48	4,73
S II area (40,43)	R	60	−9	15	3,95				
	L	−60	−15	21	3,93				
Other cortical areas									
Middle temporal area (21)	R								
	L					−60	−57	6	4,65
Subcortical regions									
Caudate nucleus	R					15	9	15	4,81
	L					−18	9	21	4,3
Anterior part of the putamen	R	24	18	6	4,7	27	9	12	5,47
	L	−30	6	6	5,73	−27	6	12	5,57
Posterior part of the putamen	R	27	−9	12	3,25				
	L	−33	−3	6	4,2				
Thalamus	R	15	−12	9	4,83				
	L	−18	−15	9	4,67				
Cerebellum	R	21	−45	−18	5,35				
	L	−27	−45	−18	6,23				

Coordinates are in millimeters, relative to the anterior commissure, corresponding to Talairach and Tournoux atlas. L = left; R = right; SMA = supplementary motor area. Activation differences were considered significant at $P < 0.001$ if their spatial extent was >18 voxels or 172 mm^3 ($P < 0.05$ corrected for multiple comparison).

was found in the right or left primary motor areas, while other newly activated regions were observed.

The frontal lobes showed activation in the left dorsolateral prefrontal area (BA 9 and 46) and in the right rostral prefrontal area (BA 10 and 11).

In the parietal lobe, a large activation of the superior areas (BA 7) was observed, extending more caudally (y coordinate of maximal Z value = −54 and −60 in the right and left hemispheres, respectively) than those activated during executed movements (y coordinate of maximal Z value = −36 and −42 in the right and left hemispheres, respectively). Significant activation was also detected in the rostral area 40 of the inferior parietal lobe close to the post-central gyrus, whereas no activation was found in the ventral inferior parietal area (BA 40 and 43).

In the basal ganglia, the activation sites were located more rostrally than those described during movement execution. The caudate nucleus and the anterior part of the putamen were activated during mental simulation, whereas no activation was found in the posterior part of the putamen.

The middle part of the left temporal lobe (BA 21) and bilateral inferior frontal areas (BA 44/45) were also activated.
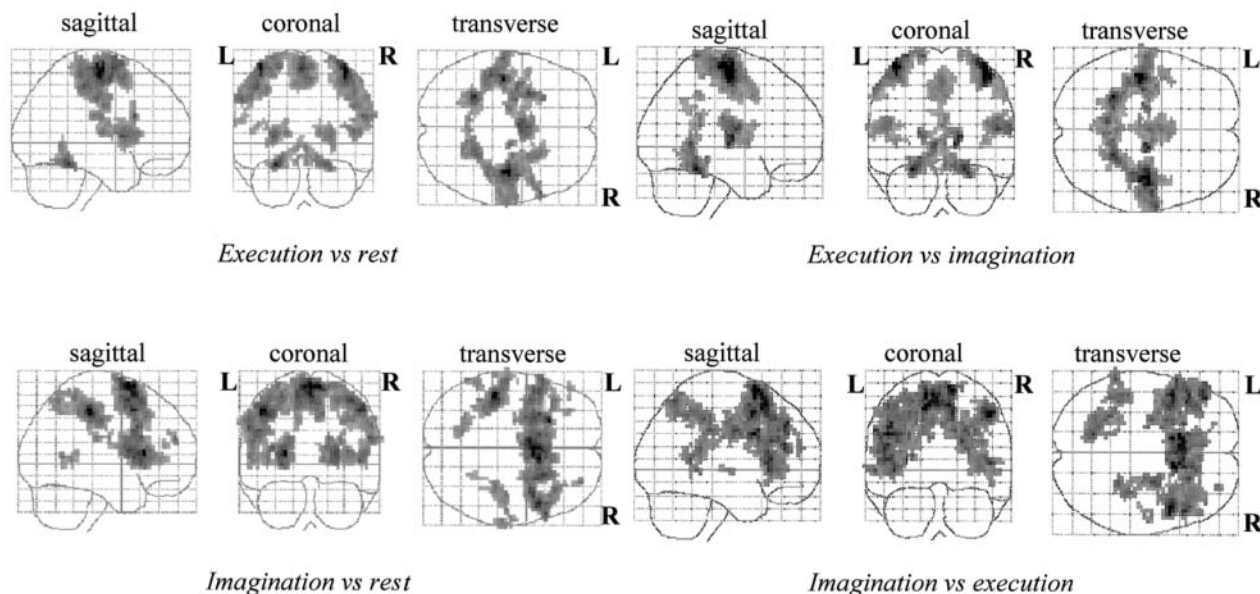
Execution Compared with Imagination of Movement
The direct comparison between executed and imagined movement showed a significant network of activation, centered on the central sulcus (Table 2, Figures 1 and 2). This network included, bilaterally, the sensorimotor and the lateral PM cortex, the post-SMA and the anterior cingulate cortex (BA 24), and the ventral inferior parietal areas (BA 40 and 43).

At the subcortical level, activation was found in the anterior part of the right putamen and in the posterior part of the left putamen. Activation was also detected in the ventrolateral nucleus of the thalamus bilaterally and the rostral part of the cerebellar cortex (Figure 3).

Imagination Compared with Execution of Movement
Areas activated during imagined movements surrounded the activation sites observed during the executed movements, being more rostral in the frontal lobes and more superior and caudal in the parietal cortex (Table 2, Figures 1 and 2). Activation was particularly important in the superior and inferior parietal cortex (BA 7, 40), the prefrontal cortex (BA 46, 9 and 10, 11), and the pre-SMA. The frontal lobe also showed activation in the

Figure 1. Statistical parametric maps (SPMs) of the group analysis (random effect) for execution compared with rest (upper row, left), imagination compared with rest (lower row, left), execution compared with imagination (upper row, right) and imagination compared with execution (lower row, right). Z-maps were first thresholded at $Z = 3.09$ ($P < 0.001$). In these thresholded maps, activated clusters were considered significant if their spatial extent was >18 voxels (or 172 mm^3), corresponding to a risk of error (type I error) of $P < 0.05$. Pixels are displayed on a gray scale (lower Z scores, light gray; higher Z scores, dark gray). The SPMs are displayed on Talairach space as a maximum intensity projection (all pixels activated in the cortical surface as well as in the deep structures are visible as if viewed in transparency through the brain) viewed from the right side (sagittal), the back (coronal) and the top (transverse) of the brain.

lateral PM cortex bilaterally and in the right anterior cingulate cortex (BA 32). Activation in the parietal lobes was left-sided (BA 7 and 40).

Significant activation in the middle temporal area and the caudal inferior frontal cortex (BA 44) was also detected.

In the basal ganglia, activation was rostral to the VCA line. The anterior part of the putamen was activated in the left hemisphere, whereas the head of the caudate nucleus was activated in the right hemisphere though with a lower threshold ($P = 0.01$, non-corrected). No activation was detected in the thalamus or the cerebellum (Figure 3).

Complex Movements Compared with Simple Movement
The comparisons between complex and simple movement, and between simple and complex movements showed no significant activation.

Results in Individual Subjects
Analysis of individual data is presented in Table 3. Individual analysis allowed us to study inter-subject variability of activated areas as well as the correspondence between anatomy and activation, which was of particular interest in the parietal lobe, the SMA and the basal ganglia.

Actual execution compared with imagination was associated with activation in the primary motor cortex in all subjects. Activation in the motor cortex was located in the anterior bank of the central sulcus, in the hand motor area (hand knob). No activation was found in the motor cortex when imagination was compared directly with execution. However, when imagination was compared with rest, four subjects showed activation in the primary motor cortex, three in the right hemisphere and four in the left.

In the SMA, when comparing imagination with execution and execution with imagination, the group pattern was seen in all eight subjects (Figure 4). Activation observed during imagination of movement was located in the pre-SMA while during execution in the post-SMA. Only one subject showed activation in the post-SMA during imagination, although the pre-SMA was more significantly activated in the same subject (pre-SMA: $Z = 7.50$ and 7.56; post-SMA: $Z = 6.22$ and 6.75 in the left and right hemispheres, respectively). In addition, when each experimental task (imagination and execution) was contrasted to the rest condition, a rostro-caudal gradient was found in the post-SMA, in two and six out of the eight subjects in the right and the left hemispheres, respectively. Therefore, the caudal part of the post-SMA was more specifically involved during execution and the rostral part during imagination (mean y during execution: right = –7.2 and left = –6.54; and imagination: right = –6 and left = –3, Student's t-test, $P < 0.05$).

In the lateral PM area (BA 6), activation observed during imagination was more rostral than during execution. Only one subject presented an activation more rostral during the execution than the imagination, located in BA 8 (Figure 4). As in the group results, prefrontal areas were more activated during the imagination than during the execution of hand movements (Table 3).

In the parietal lobe, the individual results confirmed the existence of a functional dissociation between the areas involved in motor imagery and those implicated in motor execution (Table 3). During imagination, activation was restricted to the caudal part of the superior and inferior parietal regions (BA 7 and 40), while actual execution was associated with more rostral and bilateral activation in the inferior and the superior parietal lobe (SI and SII areas). Anatomically, the posterior parietal area, which was more activated during imagination, was divided into a superior and an inferior region. The superior region corresponded to BA 7 close to the posterior part of the intra-parietal sulcus. The post-central sulcus, the lateral and the horizontal part

Table 2

Coordinates of significant cluster maxima in the group analysis for executed movement compared with imagined movement and for imagined movement compared with executed movement

| Anatomic Areas (Brodmann area)	Hemisphere	Executed movement with rest compared				Imagined movement with rest compared			
		X	Y	Z	Z-score	X	Y	Z	Z-score
Prefrontal cortex									
Dorsolateral prefrontal area (9,46)	R								
	L					−57	42	15	4,74
Rostral prefrontal area (10,11)	R					27	54	18	4,22
	L								
Inferior frontal area (44,45)	R					51	36	0	4,05
	L					−57	21	6	4,56
Motor and premotor cortex									
Primary motor area (4)	R	39	−15	63	7,22				
	L	−42	−18	69	7,19				
Lateral premotor area (6)	R	24	−9	75	4,28	48	9	48	5,87
	L	−36	−6	69	4,53	−42	3	51	4,57
Medial premotor area (6)									
Pre-SMA	R					9	18	54	5,48
	L					−6	18	63	5,63
Post-SMA	R	3	0	57	4,13				
	L	−3	−3	57	4,64				
Parietal area									
Primary sensory area (1,2,3)	R	48	−30	60	4,28				
	L	−51	−18	60	5,37				
Superior parietal area (7)	R								
	L					−15	−63	57	4,97
Inferior parietal area (40)	R								
	L					−48	−36	42	4,69
S II area (40,43)	R	51	−9	15	5,88				
	L	−51	−15	15	5,07				
Other cortical areas									
Middle temporal area (21)	R					57	−12	0	3,88
	L					−60	−42	0	4,81
Cingulum area (32)	R	3	6	42	4,59	6	24	27	3,42
	L	−6	9	42	4,34				
Subcortical regions									
Caudate nucleus	R					9	15	3	3,83*
	L								
Anterior part of the putamen	R	30	3	0	3,09*				
	L					−24	3	18	3,67
Posterior part of the putamen	R								
	L	−30	−3	3	4,08				
Thalamus	R	15	−12	9	6,31				
	L	−18	−15	9	5,5				
Cerebellum	R	21	−45	−18	6,1				
	L	−27	−45	−18	6,57				

Coordinates are in millimeters, relative to the anterior commissure, corresponding to Talairach and Tournoux atlas. L = left; R = right; SMA = supplementary motor area. Clusters are defined with height threshold (u) = 3.09, P = 0.001, and extent threshold (k) = 18 voxels, corresponding to a 5% risk of error, corrected for multiple comparisons, except for * which are thresholded at (u) = 2.33, P = 0.01 uncorrected for multiple comparison. (See rationale in the Materials and Methods section.)

of the intra-parietal sulcus limited the inferior region. We also identified anatomically the regions more activated during actual execution of movement. SI area extended from the posterior bank of the central sulcus to the post-central sulcus (BA 1, 2, 3). SII was located in the depth of the Sylvian fissure and the opercular area, bounded rostrally by the central sulcus (BA 40 and 43).

Interestingly, activation in the parietal cortex during imagination largely predominated in the left hemisphere (Figure 4). All subjects but one presented a focus of activation located in the left inferior parietal cortex, whereas only two had a similar activation in the homologous region of the right hemisphere with a lower statistical significance than in the left hemisphere. In the superior parietal cortex, one subject activated the left hemisphere only and five out of eight subjects presented foci of activation in both hemispheres, with a higher statistical significance on the left side (mean Z score across subjects = 6.32 ± 0.99 and 5.19 ± 1.71 in the left and right hemispheres, respectively, P = 0.03, Student's t-test). During movement execution, both parietal lobes were activated symmetrically.

Analysis of individual data showed that distinct subcortical structures were involved when executed and imagined movements were compared with rest. During imagination, there was a prominent activation located in the head of the caudate nucleus and the anterior part of the putamen, whereas during movement execution activation was mainly found in the anterior and posterior parts of the putamen (Table 3). Therefore, the caudate nucleus was more specifically activated during motor imagery whereas the posterior part of the putamen was more specifically activated during the actual performance of the movement, and the anterior part of the putamen was equally activated in both conditions. Activation in the caudate nucleus during movement imagination was associated with prefrontal activation in seven out of eight subjects.

The comparison between complex and simple movements showed a significant number of foci in the parietal cortex, and fewer in the premotor cortex (Table 3). In the parietal lobes, activation in the primary sensory area was observed in six and four subjects in the right and left hemispheres, respectively. Activation in the posterior parietal areas was largely predom-
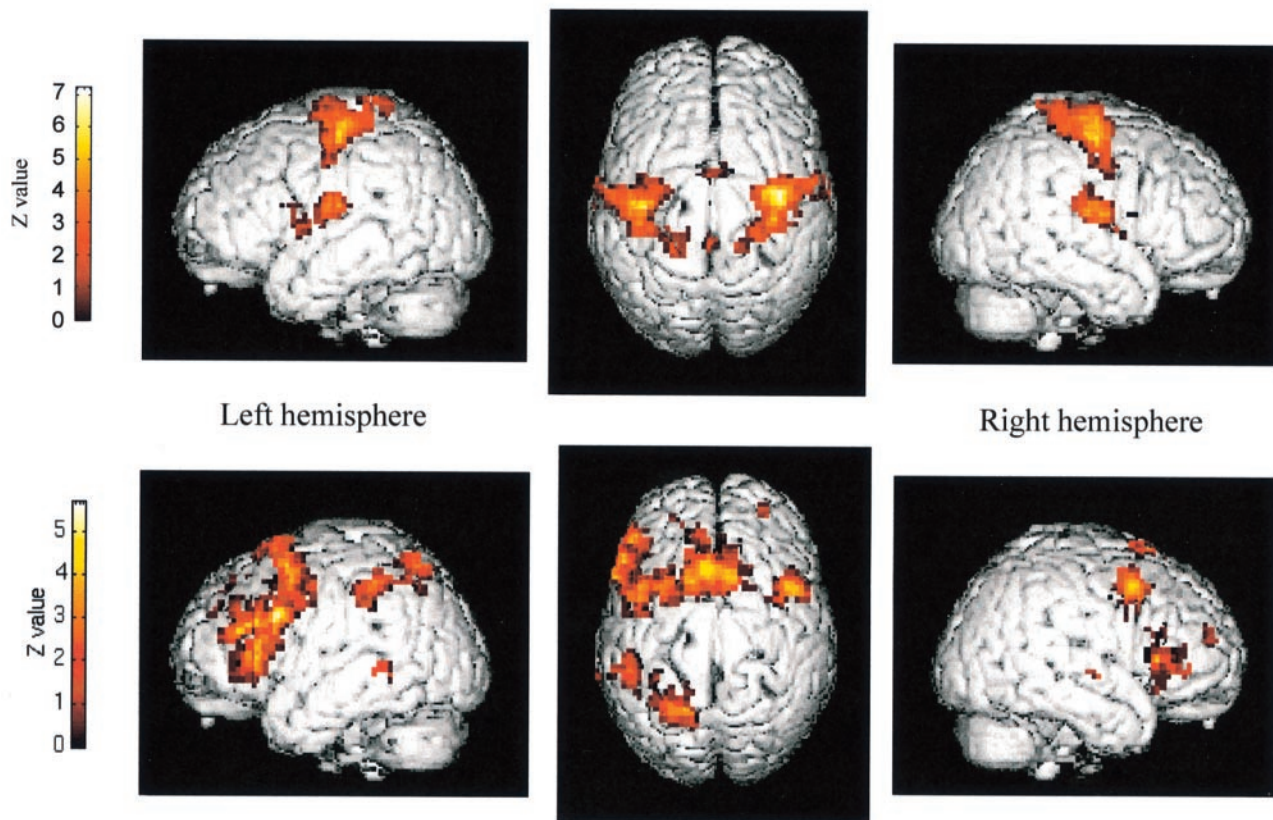
Figure 2. Activation maps from group study is superimposed on the three-dimensional surface rendering of the MNI template (SPM96). These renderings show only those pixels which are present at the surface of the brain. Significant clusters are defined as in Figure 1. For execution compared with imagination (upper row), activation was centered in the central sulcus (frontal areas BA 4 and 6 and parietal areas BA 1–3, 40 and 43). For imagination compared with execution (lower row), activation surrounded activation observed during the executed movements (frontal areas BA 6, 44, 9 and 46, 10 and 11; parietal areas BA 7 and 40).

inant in the left hemisphere (one in the right, six in the left). Thus, the left parietal cortex was more specifically activated during complex movements. The comparison between simple and complex movements was not associated with any significant increase of regional cerebral blood flow.

Discussion

A common model of motor imagery, based on neuropsychological and imaging data (Rao *et al.*, 1993; Decety *et al.*, 1994; Jeannerod, 1994, 1999; Stephan *et al.*, 1995; Grafton *et al.*, 1996a), postulates that the mental representation of a motor act and its actual execution involve the activation of similar brain areas, the difference being at the final motor output stage which is not expressed during motor imagery. The results of the present study partially confirm this idea. Common cerebral structures were activated during both execution and imagination, including fronto-parietal, subcortical and cerebellar areas.

However, when imagination was directly compared with execution a specific circuit underlying motor imagery was found. Imagination of movement involved rostral premotor and prefrontal areas and caudal regions in the parietal cortex, whereas execution was predominantly associated with activation in areas located around the central sulcus. Likewise, in the basal ganglia, activation in the head of the caudate nucleus was more closely associated with motor imagery while the posterior part of the putamen was mainly involved in motor execution.

As expected, we found a predominant role of the left posterior parietal cortex during mental simulation.

Thus, our results show a shift of the metabolic signal along an antero-posterior gradient within the parietal lobe and along a postero-anterior gradient within the frontal cortex from execution to imagination of a movement.

Parietal Cortex

One of the main findings of the present study was that functionally distinct regions of the parietal lobes subserved execution and imagination of hand movements. The primary (BA 1, 2, 3) and secondary sensory areas (SII, BA 40 and 43) were more activated during the execution of movement, whereas both the superior and the inferior parietal cortex (BA 7 and 40) were more closely associated with imagination.

Activation in the posterior parietal regions obtained in the comparison of imagination with rest is in agreement with previous data on cerebral activation during hand movement. Several imaging studies have reported an activation in the superior (BA 7) or inferior parietal lobules (BA 40) in subjects performing motor imagery tasks (Decety *et al.*, 1994; Stephan *et al.*, 1995; Grafton *et al.*, 1996a). However, none of these studies demonstrated additional activation in parietal areas during imagination with respect to execution.

The specific role of the parietal cortex in movement ideation which emerges here is consistent with neuropsychological studies. Left parietal lobe lesions produce apraxia, an impair-
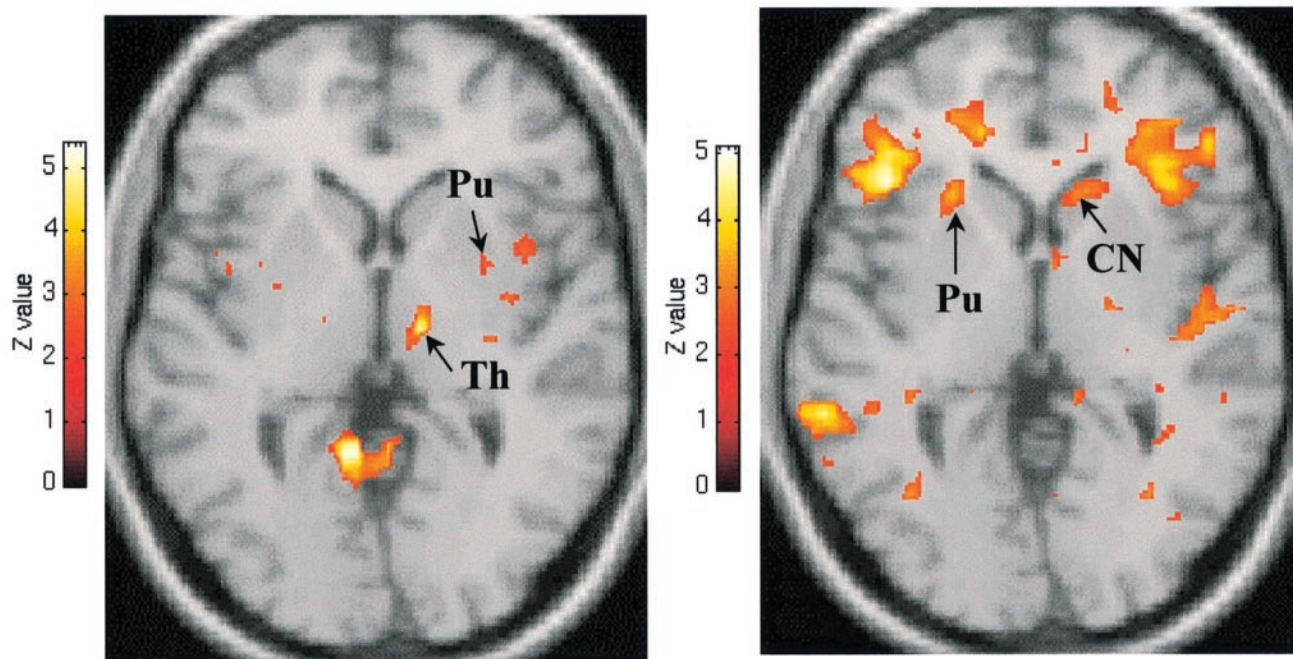
Figure 3. Activation maps of the basal ganglia from group study are superimposed on MNI template slices parallel to the AC–PC line (SPM96). Activation maps parameters are height threshold $Z = 2.33$ ($P < 0.01$), uncorrected for multiple comparison. For execution compared with imagination (left), activation was found in the putamen (Pu) and the thalamus (Th) (the image plane is located 3 mm above the AC–PC plane). For imagination compared with execution (right), activation was located more anteriorly in the putamen and in the caudate nucleus (CN) (the image plane is located at the level of the AC–PC plane).

ment of skilled movements, in the absence of elementary sensory or motor deficits. Patients with apraxia have difficulties in performing hand movements, such as symbolic gestures (DeRenzi *et al.*, 1982) and object pantomimes, that need to be guided by internal representations (Clark *et al.*, 1994). Parietal lesion can affect both motor production and ideation, since these patients are also unable to recognize the meaning of gestures (Heilman *et al.*, 1982; Sirigu *et al.*, 1995b). Recently, Sirigu *et al.* (Sirigu *et al.*, 1996), using different hand motor tasks, showed that parietal-lesioned patients were unable to match their actual movement duration during mental imagery, suggesting that what might be altered in these patients is an internal representation of learned manual motor synergies. Thus, the parietal cortex could play a crucial role in the generation of mental motor images (Sirigu *et al.*, 1996). The results of the present study further corroborate the neuropsychological data and provide, at least for the type of movements studied here, anatomical evidence for the existence of areas within the parietal lobe specifically devoted to movement imagery.

An important aspect of the parietal involvement in movement imagery is the predominant role of the left parietal lobe. Only the left, but not the right, parietal lobe was more activated during imagination compared with execution of both right and left hand movements. To our knowledge, such a predominance of the left parietal lobe in motor imagery has not been reported in previous fMRI studies. This result is in accordance with previous studies which showed that only lesions of the left parietal lobe can produce bilateral apraxia (De Renzi *et al.*, 1982; Heilman *et al.*, 1982) and motor imagery impairment for both hands (Sirigu *et al.*, 1996). The predominance of the left parietal lobe activation was also found to be associated with movement complexity.

Two parietal areas were more activated during movement

execution than during imagery: the primary sensory areas and the parietal operculum. The primary sensory areas were activated in all subjects during execution and imagination (when these two conditions were compared with rest), in agreement with a recent fMRI study (Porro *et al.*, 1996). Activation of SI may reflect sensory feedback processes. The lack of activation in SI during imagery (compared with execution) suggests that this area was not essential for mental simulation. An additional area located in the parietal operculum was activated only during execution. This area may correspond to the second somatosensory area (SII). In monkeys, microstimulation in this region trigger contralateral limb and head movements (Mori *et al.*, 1985). A previous PET study (Grafton *et al.*, 1996b) showed that SII activation was significantly greater during grasping than pointing, suggesting that SII may play a role in the tactile exploration of objects. SII activation has also been observed during simple self-paced hand movement (Lehéricy *et al.*, 1998), suggesting that it may be involved in even more simple aspects of sensory control.

Lastly, when comparing complex and simple movements by combining both task conditions (execution and imagination), individual subjects' analysis showed a significant number of activation foci in the parietal cortex (primary sensory and posterior parietal areas). The specific involvement of the parietal cortex for complex movements is in line with a previous PET study which showed that in normal subjects the execution of a sequential finger movement increasing in complexity is associated with a growing metabolic signal within these areas (Catalan *et al.*, 1998). Our findings are also in agreement with the results obtained in patients with parietal lesions who showed a more severe impairment in mentally imagining complex movements rather than simple ones (Sirigu *et al.*, 1996). Thus, the parietal cortex may contribute to the integration of sensory

Table 3

Number of subjects who presented significant clusters for each of the six contrasts

Anatomic areas (Brodmann area)	Side	Executed movement versus rest	Imagined movement versus rest	Executed versus imagined movement	Imagined versus executed movement	Complex versus simple movement
Prefrontal cortex						
Dorsolateral prefrontal area (9,46)	R	6	6		3	
	L	4	7	2	6	
Rostral prefrontal area (10,11)	R		5	1	4	
	L	1	5	3	5	
Inferior frontal area (44,45)	R	7	7	1	1	
	L	8	7	2	2	
Motor and premotor cortex						
Primary motor area (4)	R	8	3	8		
	L	8	4	7		
Lateral premotor area (6)	R	8	8	6	6	2
	L	8	8	4	8	1
Pre-SMA (6)	R	7	8	3	8	
	L	7	8	3	8	2
Post-SMA (6)	R	5	2	8	1	
	L	7	7	8	1	
Parietal area						
Primary sensory area (1,2,3)	R	8	8	8		6
	L	7	6	8		4
Superior parietal area (7)	R	4	7	3	5	1
	L	6	8	2	6	3
Inferior parietal area (40)	R		6		2	
	L	1	6	1	7	3
S II area (40,43)	R	8		7		
	L	8		8		
Other cortical areas						
Middle temporal area (21)	R	6	5	4	1	
	L	5	5	2	1	
Cingulum area (32)	R					
	L					
Subcortical regions						
Caudate nucleus	R	3*	8*			
	L	2*	4*	1*		
Anterior part of the putamen	R	6*	7*			
	L	6*	8*		1*	
Posterior part of the putamen	R	5*		2*		
	L	4*	2*	1*	1*	
Thalamus	R	4*	2*	3*		
	L	3*	2*	1*		
Cerebellum	R	7	6	8	3	1
	L	7	6	8	4	1

No subject showed any activation when we compared simple with complex movements. Clusters are defined with height threshold (u) = 3.09, P = 0.001, and extent threshold (k) = 18 voxels, corresponding to a 5% risk of error, corrected for multiple comparisons, except for basal ganglia structures (*) which are thresholded at (u) = 2.33, P = 0.01 uncorrected for multiple comparison. (See rationale in the methods section.)

information into the ongoing movement or to an important attentional recruitment associated with complex movements (Jenkins *et al.*, 1994).

Frontal Cortex

Primary Motor Area
During movement execution the primary motor cortex was constantly activated in the region known as the hand area (Yousry *et al.*, 1997). In contrast, no activation was observed in the primary motor cortex when imagination was compared with execution. However, individual subject analysis showed that four out of the eight subjects significantly activated this region when imagination was compared with rest. The activity in M1 during movement imagination was not related to muscular contractions, as no consistent increase of EMG activity response was recorded during imagination (see Materials and Methods). These data suggest that M1 does not play a predominant role in motor imagery, although it may be activated in individual subjects. These findings are consistent with recent imaging studies, which reported a less significant activation of M1 during imagined than

actual movements in control subjects (Lang *et al.*, 1996; Porro *et al.*, 1996; Roth *et al.*, 1996; Schnitzler *et al.*, 1997). They are also in line with studies in patients, which showed that imagination of movement was not impaired in patients with motor cortical damage (Sirigu *et al.*, 1995a).

Supplementary Motor Area
In our study, the SMA showed two functional subdivisions. First, in the post-SMA, we found a rostro-caudal gradient between imagined and executed movement. This pattern was restricted to the left hemisphere in individual subject analysis. Second, the pre-SMA was more specifically involved in imagination of movement.

A functional subdivision of the post-SMA for real and virtual movements has already been reported (Tyszka *et al.*, 1994; Stephan *et al.*, 1995; Grafton *et al.*, 1996a). In monkeys, area F3, which is considered to be the homologue of the post-SMA, is strongly connected with superior parietal areas (Rizzolatti *et al.*, 1998). Thus, the left-lateralized activation within the post SMA observed during motor imagery may be related to the left dominant activation we also found in the superior parietal lobe.
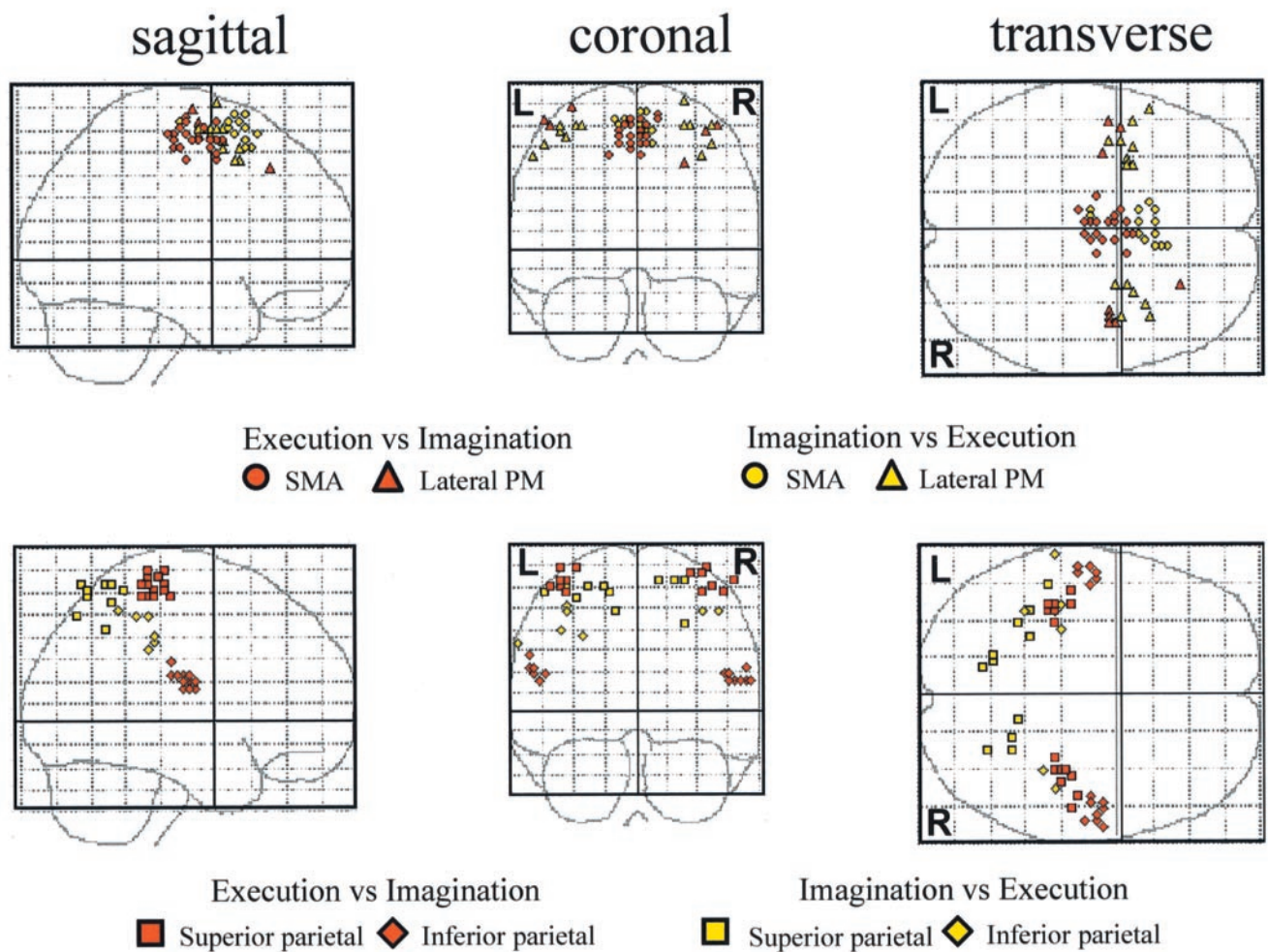
Figure 4. Glass brain plots for each subject, in Talairach space, of activation observed in the premotor cortex (PM) and the supplementary motor area (SMA) (upper row), and in the parietal lobes (lower row). Activation during imagination of movement was more rostral in the SMA (mean *Y* Talairach coordinates for maximal activity in all subject during execution: right = –5.25 and left = –5, and during imagination: right = 4 and left = 5.25) and in the PM cortex (mean *Y* coordinates for maximal activity in all subject during execution: right = –5.4 and left = –6, and during imagination: right = 5.5 and left = 4.125), and more caudal in parietal cortex than during the execution of movement. Significant clusters are defined as in Figure 1.

Previous reports have shown that the pre- and post-SMA are activated differentially during motor tasks depending on the type of movements, with the pre-SMA more involved in the selection (Deiber *et al*., 1992) and preparation of movement (Humberstone *et al*., 1997) while the posterior part is more active during execution (Deiber *et al*., 1992; Stephan *et al*., 1995; Lehéricy *et al*., 1998) and movements initiation (Passingham, 1997). The present data suggest a role of the pre-SMA in movement imagination.

Thus, the supplementary motor area consisted of three distinct functional areas: the pre-SMA, which plays a role in motor control at a high representational level; the rostral part of the post-SMA, which is also implicated in motor imagination; and the caudal part of the post-SMA, which is more closely tied to motor execution. The anatomical subdivision of this functional architecture was provided by a recent cytoarchitectonic study (Vorobiev *et al*., 1998).

Premotor and Prefrontal Cortex
In the lateral premotor cortex, a rostro-caudal gradient similar to the one found in the SMA was observed in most of the subjects as well as in the group data. Previous studies have already

reported lateral premotor activation during movement imagination (Rao *et al*., 1993; Decety *et al*., 1994; Stephan *et al*., 1995). Stephan *et al*. (Stephan *et al*., 1995) suggested that activation of the anterior part of the premotor cortex might be more important during imagination rather than execution, although they did not find such a gradient in the direct comparison of the two experimental conditions. In humans, the posterior part of the premotor cortex (BA 6) may correspond to areas F2 and F4 in the monkey, which send direct outputs to the spinal cord (Rizzolatti *et al*., 1998). These data are in a good agreement with the functional specificity of the posterior area 6 during the execution of movement. On the other hand, the anterior part of the premotor cortex may correspond to areas F5 and F7 in the monkey, which do not project to the spinal cord. This area, in association with the anterior cingulate cortex, may be involved in cognitive aspects of motor processes such as movement imagination, as our data suggest, movement selection (Deiber *et al*., 1992) or suppression of a motor response (Krams *et al*., 1998).

Activation in BA 44 was observed in most of the subjects, and has been described previously during imagination of grasping (Grafton *et al*. 1996a). This region, which seems to be the

homologue of area F5 in monkeys, may play a role during both imagination and execution of hand movement, as our data seem to suggest. Activation in BA 45 was found during the observation of a hand movement (Grafton *et al.*, 1996a; Rizzolatti *et al.*, 1996; Decety *et al.*, 1997), suggesting that BA 45 also plays a role in action recognition.

Lastly, group data, as well as individual subject analysis, showed activation in the lateral prefrontal cortex mainly during imagination (BA 9, 10, 11 and 46). Previous neuroimagery studies in humans have shown that the dorsal prefrontal cortex is activated when the subject has to make a decision, such as which finger to move (Frith *et al.*, 1991) or when to start a finger movement (Jahanshahi *et al.*, 1995). In monkeys, the area F6 is strongly connected with the dorsolateral prefrontal cortex (Luppino *et al.*, 1993). These data are consistent with the fact that these two areas were both activated during movement imagination.

Frontal and Parietal Activation: a Functional Loop for Hand Movement Representation?

The conjunction of premotor and parietal cortex activation during motor imagery is consistent with anatomical data. In monkeys, the intraparietal sulcus is richly connected to the premotor cortex (Johnson *et al.*, 1996; Matelli *et al.*, 1998). Neurophysiological studies show matching patterns of neuronal activity within the parietal and the frontal cortex. Chafee and Goldman-Rakic have demonstrated that during an oculomotor delayed task, response profiles in both the parietal and the frontal regions showed comparable temporal duration and spatial tuning (Chafee and Goldman-Rakic, 1998). In a more recent study, the same authors have showed that inactivation by cooling the parietal cortex changed significantly the activity of frontal neurons during the cue, the delay and the saccade period. Likewise, inactivation of the prefrontal cortex equally affected the behavior of parietal neurons (Chafee and Goldman-Rakic, 2000). Although exact homologies between the parietal and frontal regions of monkeys and humans are not yet fully established, it is reasonable to assume that, as in monkeys, the human parietal and frontal areas are organized as a tightly coupled functional system with highly specific connections between their respective anatomical subdivisions. Parietal areas could constitute the neural substrate for the storage of visual and kinesthetic limb postures, and for mapping these representations onto the premotor and motor regions which contain the corresponding motor programs (Sirigu *et al.*, 1996). Through reciprocal connections, the movement forms activated in the posterior parietal cortex by a visual stimulus (or by mental imagery) can be interpreted as a particular motor action via the activation of premotor cortical neurons such as the mirror neurons described by Rizzolatti and his co-workers in area F5 of the premotor cortex (Di Pellegrino *et al.*, 1992; Gallese *et al.*, 1996; Rizzolatti *et al.*, 1998).

The metabolic gradient we describe here within the fronto-parietal network is similar to what has been described by neurophysiological studies in the monkey's brain. Premotor and parietal regions contain neurons with both motor and sensory properties organized along a gradient, following a sensory-to-motor rostro-caudal representation in the lateral premotor cortex and a motor-to-sensory rostro-caudal gradient in the superior parietal cortex (Johnson *et al.*, 1996) [for a review see (Wise *et al.*, 1997)]. On the basis of these neurophysiological findings, Burnod *et al.* (Burnod *et al.*, 1992, 1999) recently proposed a computational model of this fronto-parietal circuit composed of neurons arranged into a single layer around three main axes: visual–somatic, position–direction and sensory–motor. According to the authors, these properties reflect the computation performed by local networks. This conceptual framework presents a striking parallel with the results of the present study, and suggests that a purely representational activity (motor imagery) weighs more heavily the contribution of the portions of the sensorimotor network which are concerned with movement ideation and planning, while motor execution weighs more heavily the contribution of the regions within the network which are closest to the motor output.

Basal Ganglia

Comparing imagination and execution of hand movements revealed functional differences in the basal ganglia. During real movements, activation was mainly found in the post-commissural portion of the putamen, as previously reported (Jueptner *et al.*, 1997; Lehéricy *et al.*, 1998). In non-human primates, this part of the striatum constitutes the sensorimotor territory (Alexander *et al.*, 1986; Albin *et al.*, 1989; Brooks, 1995; Parent and Hazrati, 1995) and receives afferents from the primary sensory motor cortex. In contrast, movement simulation activated a more rostral area in the head of the caudate nucleus, which receives afferents from the dorsolateral prefrontal cortex and is considered to be part of the 'associative' region of the striatum. Thus, execution and imagination in the basal ganglia engaged different areas belonging to two distinct functional cortico-subcortical loops, sensori-motor and cognitive respectively, as described in monkeys (Kunzle, 1975; Alexander *et al.*, 1990). However, these results were obtained using a lower statistical threshold ($P < 0.01$) and thus need to be confirmed in a larger number of subjects.

Activation was also present in the ventrolateral part of the thalamus, which receives pallidal, cerebellar and somesthesic inputs, and projects back to the motor cortex and the supplementary motor area.

The role of the caudate nucleus in motor imagination remains to be determined. Activation in the caudate nucleus has been reported previously during mental simulation of grasping (Decety *et al.*, 1994) and explicit learning of a sequence of key-presses (Jueptner *et al.*, 1997). However, disruption of the nigro-striatal dopaminergic system in patients with Parkinson's disease does not alter motor imagery, as they simulate movements as slow as actual ones (Dominey *et al.*, 1995). Thus, the contribution of the basal ganglia, though important in movement representation, is perhaps not instrumental in the generation of motor images.

In conclusion, our results show that, although imagination and execution of hand movements activate a large overlapping network of cerebral areas, a number of cortico-subcortical regions are more specifically devoted to hand motor imagery. These areas may constitute an important circuit for anticipating or predicting the sensory consequences of the movement. A question that now arises is why motor imagery mechanisms may have evolved this way. A possible speculation is that these neural mechanisms may have evolved in parallel with the motor preparation system to optimize learning of difficult motor tasks. When we are going to do something risky or potentially harmful, rehearsing the action allows us to try out different possibilities and may help deciding on the better strategy, when we cannot afford to go by trial and error. Such a system would in this case be essential for our survival.

References

Albin RL, Young AB, Penney JB (1989) The functional anatomy of basal ganglia disorders. Trends Neurosci 12:366–375.

Alexander GE, De Long MR, Strick PL (1986) Parallel organization of functionally segregated circuits linking basal ganglia and cortex. Annu Rev Neurosci 9:357–381.

Alexander GE, Crutcher MD (1990) Functional anatomy of basal ganglia circuits: neural substrates of parallel processing. Trends Neurosci 13:266–271.

Brooks DJ (1995) The role of the basal ganglia in motor control: contributions from PET. J Neurol Sci 128:1–13.

Burnod Y, Grandguillaume P, Otto I, Ferraina S, Johnson PB, Caminiti R (1992) Visuomotor transformations underlying arm movements toward visual targets: a neural network model of cerebral cortical operations. J Neurosci 12:1435–1453.

Burnod Y, Baraduc P, Battaglia-Mayer A, Guigon E, Koechlin E, Ferraina S, Lacquaniti F, Caminiti R (1999) Parieto-frontal coding of reaching: an integrated framework. Exp Brain Res 129:325–346.

Catalan JC, Honda M, Weeks RA, Cohen LG, Hallett M (1998) The functional neuroanatomy of simple and complex sequential finger movements: a PET study. Brain 121:253–264.

Chafee MV, Goldman-Rakic PS (1998) Matching patterns of activity in primate prefrontal area 8a and parietal area 7ip neurons during a spatial working memory task. J Neurophysiol 79:2919–2940.

Chafee MV, Goldman-Rakic PS (2000) Inactivation of parietal and prefrontal cortex reveals interdependence of neural activity during memory-guided saccades. J Neurophysiol 83:1550–1566.

Clark MA, Merians AS, Kothari A, Poizner H, Macauley B, Gonzales-Rothi L, Heilman K (1994) Spatial planning deficits in limb apraxia. Brain 117:1093–1106.

Crammond DJ (1997) Motor imagery: never in your wildest dream. Trends Neurosci 20:54–57.

Decety J, Michel F (1989) Comparative analysis of actual and mental movements times in two graphic tasks. Brain Cogn 11:87–97.

Decety J, Jeannerod M, Germain M, Pastene J (1991) Vegetative response during imagined movement is proportional to mental effort. Behav Brain Res 3:1–5.

Decety J, Perani D, Jeannerod M, Bettinardi V, Tadary B, Woods R, Mazziotta JC, Fazio F (1994) Mapping motor representations with positron emission tomography. Nature 371:600–602.

Decety J, Grezes J, Costes N, Perani D, Jeannerod M, Procyk E, Grassi F, Fazio F (1997) Brain activity during observation of actions. Influence of action content and subject's strategy. Brain 120:1763–1777.

Deiber MP, Passingham RE, Colebatch JG, Friston KJ, Nixon PD, Frackowiak RSJ (1992) Cortical areas and the selection of movement. A study with positron emission tomography. Exp Brain Res 84:393–402.

Deiber MP, Ibanez V, Honda M, Sadato N, Raman R, Hallett M (1998) Cerebral processes related to visuomotor imagery and generation of simple finger movements studied with positron emission tomography. Neuroimage 7:73–85.

Dellatolas G, De Agostini M, Jallon P, Poncet P, Rey M, Lellouch J (1988) Mesure de la préférence manuelle par autoquestionnaire dans la population française adulte. Revue de psychologie appliquée 38:117–136.

De Renzi E, Faglioni P, Sorgato P (1982) Modality-specific and supramodal mechanisms of apraxia. Brain 105:301–312.

Di Pellegrino G, Fadiga L, Fogassi L, Gallese V, Rizzolatti G (1992) Understanding motor events: a neurophysiological study. Exp Brain Res 91:176–180.

Dominey P, Decety J, Broussolle E, Chazot G, Jeannerod M. (1995) Motor imagery of a lateralized sequential task is asymmetrically slowed in hemi-Parkinson's patients. Neuropsychologia 33:727–741.

Friston KJ, Holmes AP, Worsley KJ (1999) How many subjects constitute a study? Neuroimage 1:1–5.

Frith CD, Friston K, Liddle PF, Frackowiak RS (1991) Willed action and the prefrontal cortex in man: a study with PET. Proc R Soc Lond B Biol Sci 244:241–246.

Gallese V, Fadiga L, Fogassi L, Rizzolatti G (1996) Action recognition in the premotor cortex. Brain 119:593–609.

Grafton ST, Arbib MA, Fadiga L, Rizzolatti G (1996a) Localization of grasp representations in humans by positron emission tomography. Exp Brain Res 112:103–111.

Grafton ST, Fagg AH, Woods RP, Arbib MA (1996b) Functional anatomy of pointing and grasping in humans. Cereb Cortex 6:226–237.

Heilman KM, Rothi LJ, Valenstein E (1982) Two forms of ideo-motor apraxia. Neurology 32:342–346.

Humberstone M, Sawle GV, Clare S, Hykin J, Coxon R, Bowtell R, Macdonald IA, Morris PG (1997) Functional magnetic resonance imaging of single motor events reveals human presupplementary motor area. Ann Neurol 42:632–637.

Jahanshahi M, Jenkins IH, Brown RG, Marsden CD, Passingham RE, Brooks DJ (1995) Self-initiated versus externally triggered movements. I. An investigation using regional cerebral blood flow and movement related potentials in normal and Parkinson's disease. Brain 118:913–933.

Jeannerod M (1994) The representing brain: neural correlates of motor intention and imagery. Behav Brain Sci 17:187–245.

Jeannerod M (1999) The 25th Bartlett Lecture. To act or not to act: perspectives on the representation of actions. Quart J Exp Psychol A 52:1–29.

Jeannerod M, Frak V (1999) Mental imaging of motor activity in humans. Curr Op Neurobiol (in press).

Jenkins IH, Brooks DJ, Nixon PD, Frackowiak RS, Passingham RE (1994) Motor sequence learning: a study a study with positron emission tomography. J Neurosci 14:3775–3790.

Johnson PB, Ferraina S, Bianchi L, Caminiti R (1996) Cortical networks for visual reaching: physiological and anatomical organization of frontal and parietal lobe arm regions. Cereb Cortex 6:102–119.

Jueptner M, Frith CD, Brooks DJ, Frackowiak RS, Passingham RE (1997) Anatomy of motor learning. II. Subcortical structures and learning by trial error. J Neurophysiol 77:1325–1337.

Krams M, Rushworth MF, Deiber MP, Frakowiak RS, Passingham RE (1998) The preparation, execution and suppression of copied movement in the human brain. Exp Brain Res 120:386–398.

Kunzle H (1975) Bilateral projections from the precentral motor cortex to the putamen and other parts of the basal ganglia. An autoradiographic study in macaca fascicularis. Brain Res 88:195–209.

Lang W, Cheyne D, Höllinger P, Gerschlager W, Lindinger G (1996) Electric and magnetic fields of the brain accompanying internal simulation of movement. Brain Res Cogn Brain Res 3:125–129.

Lehéricy S, Van de moortele PF, Lobel E, Paradis AL, Vidailhet M, Frouin V, Neveu P, Agid Y, Marsault C, Le Bihan D (1998) Somatotopical organization of striatal activation during finger and toe movement: a 3-T functional magneticresonance imaging study. Ann Neurol 44:398–404.

Luppino G, Matelli M, Camarda R, Rizzolatti G (1993) Corticocortical connections of area F3 (SMA-proper) and area F6 (pre-SMA) in the macaque monkey. J Comp Neurol 338:114–140.

Matelli M, Govoni P, Galletti C, Kutz DF, Luppino G (1998) Superior area 6 afferents from the superior parietal lobule in the macaque monkey. J Comp Neurol 402:327–352.

Mori A, Babb RS, Walters RS, Asanuma H (1985) Motor effects produced by stimulation of secondary somatosensory (SII) cortex in the monkey. Exp Brain Res 58:440–442.

Parent A, Hazrati LN (1995) Functional anatomy of the basal ganglia. I. The cortico-basal ganglia-thalamo-cortical loop. Brain Res Rev 20:91–127.

Passingham R (1997) Functional organisation of the motor system. In: human brain function (Frackowiak RSJ, Friston KJ, Frith CD, Dolan RJ, Mazziota JC, eds), pp. 243–274. San Diego, CA: Academic Press.

Porro CA, Francescato MP, Cettolo V, Diamond ME, Baraldi P, Zuiani C, Bazzocchi M, di Prampero PE (1996) Primary motor and sensory cortex activation during motor performance and motor imagery: a functional magnetic resonance imaging study. J Neurosci 16:7688–1698.

Rao SM, Binder JR, Bandettini PA, Hammeke TA, Yetkin FZ, Jesmanowicz A, Lisk LM, Morris GL, Mueller WM, Estkowski LD, Wong EC, Haughton VM, Hyde JS (1993) Functional magnetic

resonance imaging of complex human movements. Neurology 43:2311–2318.

Rizzolatti G, Fadiga L, Matelli M, Bettinardi V, Paulesu E, Perani D, Fazio F (1996) Localization of grasp representations in humans by PET: 1. Observation versus execution. Exp Brain Res 111:246–252.

Rizzolatti G, Luppino G, Matteli M (1998) The organization of the cortical motor system: new concepts. Electroencephalogr Clin Neurophysiol 106:283–296.

Roland PE, Skinhoj E, Lassen NA, Larsen B (1980) Different cortical areas in man in organization of voluntary movements in extrapersonal space. J Neurophysiol 43:137–150.

Roth M, Decety J, Raybaudi M, Massarelli R, Delon-Martin C, Segebarth C, Morand S, Gemignani A, Décorps M, Jeannerod M (1996) Possible involvement of primary motor cortex in mentally simulated movement: a functional magnetic resonance imaging study. NeuroReport 7:1280–1284.

Schnitzler A, Salenius S, Salmelin R, Jousmäki V, Hari R (1997) Involvement of primary motor cortex in motor imagery: a neuromagnetic study. Neuroimage 6:201–208.

Sirigu A, Cohen L, Duhamel JR, Pillon B, Dubois B, Agid Y, Pierrot-Deseilligny C (1995a) Congruent unilateral impairments for real and imagined hand movements. NeuroReport 6:997–1001.

Sirigu A, Cohen L, Duhamel JR, Pillon B, Dubois B, Agid Y (1995b) A selective impairment of hand posture for object utilization in apraxia. Cortex 31:41–56.

Sirigu A, Duhamel JR, Cohen L, Pillon B, Dubois B, Agid Y (1996) The mental representation of hand movements after parietal cortex damage. Science 273:1564–1568.

Stephan KM, Fink GR, Passingham RE, Silbersweig D, Ceballos-Baumann AO, Frith CD, Frackowiak RSJ (1995) Functional anatomy of the mental representation of upper extremity movements in healthy subjects. J Neurophysiol 73:373–386.

Tyszka JM, Grafton ST, Chew W, Woods RP, Colletti PM (1994) Parceling of mesial frontal motor areas during ideation and movement using functional magnetic resonance imaging at 1.5 tesla. Ann Neurol 35:746–749.

Vorobiev V, Govoni P, Rizzolatti G, Matelli M, Luppino G (1998) Parcellation of human mesial area 6: cytoarchitectonic evidence for three separate areas. Eur J Neurosci 10:2199–2203.

Wise SP, Boussaoud D, Johnson PB, Caminiti R (1997) Premotor and parietal cortex: corticocortical connectivity and combinatorial computations. Annu Rev Neurosci 20:25–42.

Yousry TA, Schmid UD, Alkadhi H, Schmidt D, Peraud A, Buettner A, Winkler P (1997) Localization of the motor hand area to a knob on the precentral gyrus. Brain 120:141–157.