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INTRODUCTION

The condition in which a subject consciously images and simulates a motor performance has been widely exploited (for a review see 12). Functional magnetic resonance imaging studies (fMRI) (20) and electrophysiological data (15) indicate a wide activation of the sensorimotor cortex during simulation of the movements, and a cerebellar activation during the mental imagery of complex motor actions (18). Motor imagery has also been associated with an increase of the premotor and prefrontal activity suggesting that the mental representation of the movements plays an important role in both planning and preparation stages of the performance (11). Recent fMRI reports point out that the same cortical regions are activated by pure motor imagery and by simple execution of movements (21, 22). There is however evidence that the pattern of cortical activity elicited by pure mental simulation differs from that occurring when motor imagery precedes the actual performance and it may be further changed by the mode of movements execution (4). These findings are suggestive of task-dependent functional interactions, between different neural structures involved in motor output and visuomotor imagination.

Taking into account these observations one may ask whether the mental rehearsal of movements performed immediately prior of the motor outcome may influence the pattern of activity of motor areas, compared to the simple execution. The present fMRI study addresses this question by comparing regional distribution of cortical activity during unilateral hand movements and during the same movements preceded by their mental simulation.

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METHODS

Subjects

Six healthy females aged between 23 and 32 years were enrolled into the study. In agreement with the guidelines of the local Ethical Committee, they gave informed consent to participate to the experiment. All subjects were right handed, as assessed by the Edinburgh Inventory (17) and showed a high ability in motor imagery, according to the results of the Hall and Pongrac Questionnaire (7).

Experimental paradigm

The task consisted of sequential finger movements (i.e. rhythmic tapping of each finger to the thumb) performed by the right hand. Subjects were trained to perform the finger-to-thumb opposition, back and forth, at a frequency of 1.5 Hz.

The experimental paradigm included two conditions: the condition E, which was the simple Execution of the motor task, and the condition S+E, (Simulation + Execution) in which Execution was preceded by the mental simulation of the same movements.

The E condition included a resting period (60 s of duration), during which the subject counted covertly by increments of one, followed by a period (lasting 40 s), in which the subject performed the sequential movements. The S+E condition consisted in a shorter resting period (40 s) that was followed by the mental simulation of the task (20 s) and by the actual execution of simulated movements (40 s). The shift from rest to activation period was triggered by a vocal command.

The mental simulation was performed as described by Jeannerod (10); the procedure does not imply visualization of the intended motor act since the subject is required to concentrate only on the somatic components of the task and "simply feel the self in action".

Analysis of fMRI signal was performed during the execution periods in both E and S+E conditions.

Each experimental condition was repeated three times in different fMRI runs, as depicted in Fig. 1.

Each subject provided in total 6 runs, that is 3 runs for the E condition and 3 runs for the S+E condition. The order of experimental conditions was counterbalanced across the subjects. Subjects were instructed to keep their eyes closed and to minimize wrist movements during the execution of the task; throughout the scanning series subjects' head was restrained by a conventional head-rest device.

MR acquisition

Images were acquired with a 1.5 Tesla clinical whole body scanner (Philips ACS II). The head coil was used for excitation, while the body coil was used for detection. Four axial slices parallel to the plane between the anterior and posterior commissure were sequentially acquired. Positioning of the image planes was performed on scout images acquired in the sagittal plane and the most inferior slice was positioned 45 mm above the plane.

A conventional gradient-recalled echo pulse sequence was applied (1, 22). The principle fMRI parameters of this sequence were: TR = 77 ms, TE = 40 ms, flip angle = 30°, Field of view = 154220 mm^2, slice thickness = 5 mm, spatial resolution in the image plane = 3.4 mm, acquisition matrix = 4564, reconstruction matrix = 90128, acquisition time per slice = 2.5 s, pixel bandwidth = 15 Hz. Subsequent to the functional runs, high resolution 3D anatomical and 3D phase contrast (PC) MR angiography runs were performed. These runs provided anatomical as well as vascular information about the volume of interest (24).

Functional MRI post-processing

The fMRI signals collected in the present experiment were processed according to the a procedure already used in previous studies and fully described in Roth *et al.* (22) and Baciu *et al.* (1).

The in-plane co-registration of the fMRI images, was followed by a pixelwise baseline correction of the temporal responses (1, 16, 22). Then, the power spectra of the temporal responses from each voxel were calculated and cross-correlated with the power spectrum of the experimental par-

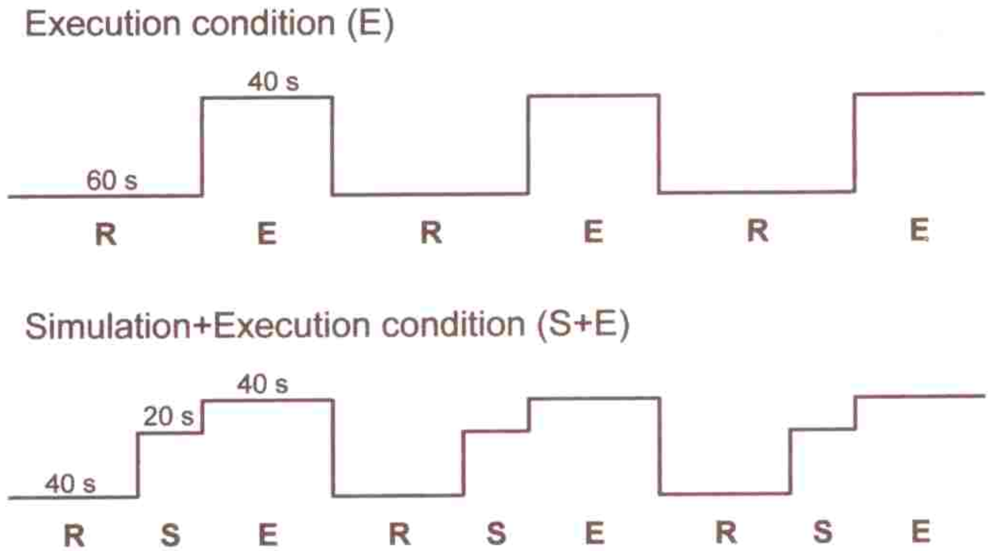

Fig. 1. - *Schematic drawing of the experimental paradigm.*

On the top is represented the E condition, simple Execution of the motor task, consisting in a resting period (R), followed by the motor outcome (E).
On the bottom is represented the S+E condition, Execution preceded by mental Simulation of the motor task, consisting in a resting period (R) followed by the mental simulation of the task (S) and by the actual execution of the simulated movements (E).

adigm (22). The z-scores of temporal responses were also calculated. The functional maps included only clusters comprising at least three adjacent "activated" voxels, which exhibited a cross-correlation factor with the paradigm > 0.7 and a z-score > 0.5 (2). Isolated activated voxels were discarded.

A blood vascular mask, derived from the three-dimensional PC MR scan, was used to identify possible macrovascular responses within the slices. In each subject the vascular masks were superimposed on the corresponding activation maps to rule out signal increments due to blood flow increase in the cortical macrovascular system (24). Finally, the functional images were superimposed onto the corresponding high-resolution anatomical images (derived from the three-dimensional PC MR scan) to localize the cortical activations. The identification of activated cortical regions was performed by visual comparison of the functional maps with the anatomical images of the Talairach and Tournoux atlas (25).

In each subject we studied three distinct cortical motor areas: primary motor cortex corresponding to the anterior bank of central sulcus (M1, Brodmann's Area 4); pre-motor area that spans from the precentral sulcus to the dorsolateral frontal lobe and includes the anterior precentral gyrus (PMA, lateral portion of Brodmann's Area 6); supplementary motor area that extends from the paracentral sulcus to cover the anterior region of the medial caudal half of superior frontal gyrus (SMA, medial portion of Brodmann's Area 6).

Statistical analysis

The consistency of cortical activation across the different runs was verified by ANOVA, having as main factors the number of voxels of each Scan, the Subjects and the Conditions. The results showed that under both the E and the S+E conditions there was no difference among the three runs, therefore the statistical analyses were performed on the total number of activated voxels measured in each subject. The data were analyzed by three-factor ANOVA for repeated measures having as independent variables the cortical Areas (M1, PMA, SMA), the Side of the brain (Contra and Ipsilateral) and the experimental Condition (E and S+E). Post-hoc comparisons were performed by two-tailed t-Tests.

Finally, the rate of activity change, that is the percent difference of functional activity in the S+E condition relative to the E condition, was calculated in each subject for each cortical area.

RESULTS

Table I contains, for each subject, the total number of activated voxels found in the hemisphere contralateral and ipsilateral to the performing hand under the two experimental conditions.

ANOVA reveals that the main variables Side and Condition are highly significant, due to the much larger number of activated voxels in the contralateral than in the ipsilateral hemisphere ($F = 44.6$, $df = 1,5$, $p = .001$) and to the generally higher activity in the S+E than in the E condition ($F = 20.1$, $df = 1,5$, $p = .007$). In Fig. 2 it is shown that the cortical activation of both hemispheres is higher in S+E than in E condition, yielding significant interaction Condition Side ($F = 33.1$, $df = 1,5$ $p = .002$). Post-hoc comparisons show that in the contralateral hemisphere the prevalent activation during the S+E condition occurs in both the PMA ($t = 4.1$, $df = 5$, $p = .010$) and M1 ($t = 3.7$, $df = 5$, $p = .014$) regions while in the ipsilateral hemisphere only the M1 is significantly more activated in S+E relative to the E condition ($t = 2.7$, $df = 5$, $p = .039$). The activity of SMA is not different in the two conditions in both hemispheres.

In each subject we computed the difference between the number of activated voxels of the S+E and the E condition. This difference of the cortical activity is represented in Fig. 3, for each region of interest. The figure shows that a significant activity enhancement occurs in both the contralateral and the ipsilateral M1 as well as in the contralateral PMA. Only for the ipsilateral PMA functional activity tends to be larger in the E than in the S+E condition although the rate of change is not significant.

Table I. - Number of voxels activated in the contralateral and ipsilateral hemisphere during E and S+E condition.

	E condition		S+E condition	
	Contralateral hemisphere	Ipsilaterai hemisphere	Contralateral hemisphere	Ipsilateral hemisphere
Subject 1	135	8	247	0
Subject 2	192	36	247	37
Sublect 3	129	0	190	13
Subject 4	177	21	340	48
Sublect 5	74	55	133	43
Subject 6	107	0	193	10
MEAN (± SEM)	135 ± 17	20 ± 9	225 ± 29	25 ± 8

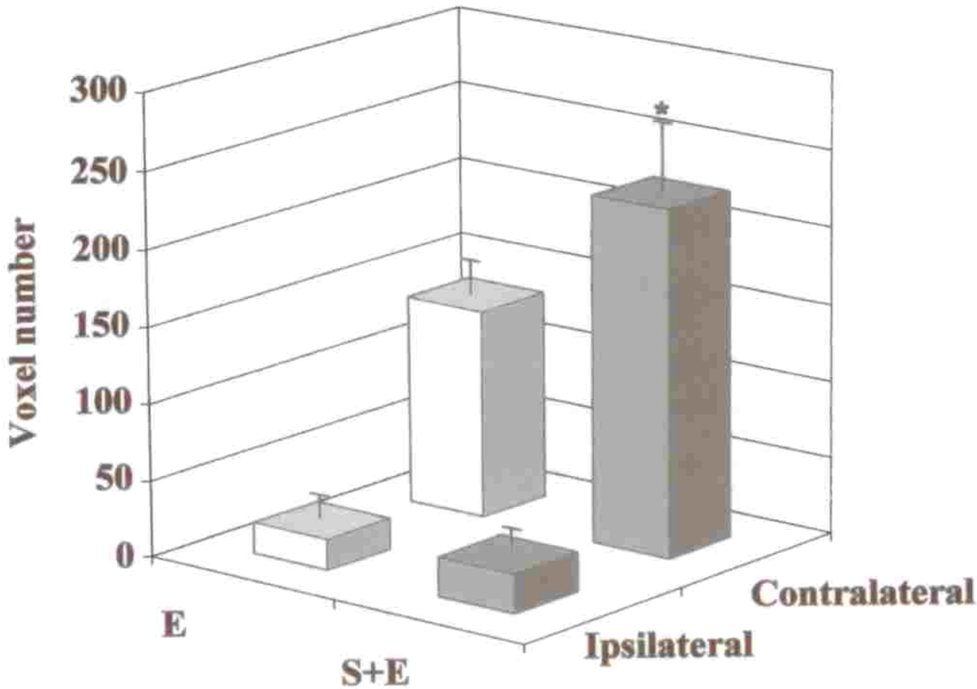

Fig. 2. - *Functional activity in the two hemispheres.*

Histograms show the total number of correlated voxels in the contralateral and ipsilateral hemisphere in the E condition (white columns) and the S+E condition (grey columns).
* S+E vs E condition $p < .05$.

DISCUSSION

The present experiment compares the functional cortical activity elicited by the execution of a finger-to-thumb opposition task (E condition) with the activity occurring when mental simulation of the task precedes the actual performance (S+E condition). We have found that the spatial distribution of activated voxels is increased in the S+E condition with respect to the E condition. This suggests that motor areas are functionally more active when the movements are performed after their mental simulation, relative to the condition without mental rehearsal.

Previous studies have reported that the pure motor imagery (19,22) as well as the simple execution of unimanual motor task (22) induces functional activation of the premotor areas (PMA) of both hemispheres. Accordingly, one may expect that the enhancement of activity occurring during the S+E condition is present on the ipsilateral as on the contralateral PMA. Our findings, while confirming the bilateral activation of PMA during the E condition, show that mental simulation has a rather different effect on the two sides of the brain. Indeed, functional activation of the contralateral PMA is significantly increased during the S+E condition with respect to

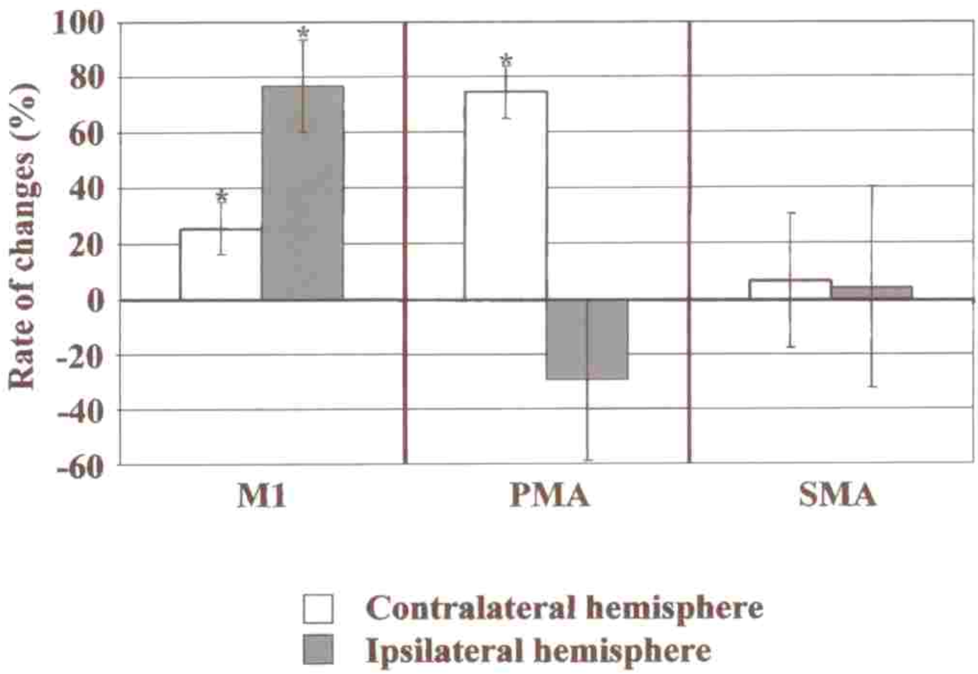

Fig. 3. - *Mean activity change.*

Difference between the number of activated voxels during S+E condition relative to the E condition for each region of interest of both hemisphere.
For each subject and for each experimental condition the activated clusters were localized according to the x, y, and z coordinates of the Talairach and Tournoux Atlas. The range of coordinates is indicated for M1, PMA and SMA of both hemispheres. Contralateral hemisphere: M1 (+32/+40, -20, +45/+65); PMA (+30, +15, +45/+65); SMA (+8/+10, -1/-20, +45/+65). Ipsilateral hemisphere:M1 (-32/-40, -20, +45/+65); PMA (-30, +15, +45/+65); SMA (-8/-10, -1/-20, +45/+65).
* S+E vs E condition = $p < .05$

the simple motor execution whereas the activity of ipsilateral PMA tends to be reduced in most of the subjects.

During the S+E condition the activity of primary motor cortex (M1) is significantly enhanced on both sides of the brain. The rate of change – that is estimated in relation to the activity in the E condition – is highest for the ipsilateral M1. The functional activation of ipsilateral M1 is rather poor during the E condition and becomes more than 7 times greater when the motor outcome follows the mental simulation of the task. In contralateral M1 the increment of activity during the S+E condition is smaller, although the total number of activated voxels is much higher than in ipsilateral M1.

Finally, the activity of supplementary motor area (SMA) during the S+E condition is virtually unchanged in both hemispheres with respect to E condition.

Our experiment does not allow a comparison between ipsilateral activity in the two hemispheres. The task was performed by the right hand only, and then ipsilateral activation could be measured only in the right hemisphere. This represents a limitation. Several reports indicate in fact that the activity of the left motor cortex during ipsilateral fingers movements is more consistent than the corresponding ipsilateral activation of the right cortex (6, 14). Given this hemispheric functional asymmetry, one may expect that the mental imagery does influence the activation of ipsilateral M1 at a different extent in the two hemispheres.

Our findings are in agreement with those results suggesting that the level of neural excitability may be increased by the motor imagery. Bonnet *et al.* (3) found increased spinal reflexes during a mentally simulated isometric foot pressure and similar results were obtained by using transcranial magnetic stimulation (TMS) of motor cortex. TMS was used to trigger motor evoked potentials (MEPs) in arm muscles during simulated arm movements and MEPs were increased only in the muscles involved in the imagined movements. (5, 8, 13). A logical consequence of increased motor cortex excitability is that it should propagate down to the motoneuron level. This is still a controversial issue, however (12).

All together these results suggest that motor performance preceded by mental rehearsal is associated to selective increases of the cortical activity. Not all the motor areas that are functionally active in simple motor execution and pure motor imagery present the enhancement of activity during the S+E condition. Changes in the pattern of cortical activity might reflect the concurrent activation of regions involved in both the preparation and the execution stage of the motor outcome. The activity change may be dependent on different factors, such as the subject's familiarity with task, the type of motor imagery and the mode of movements execution.

In conclusion, the beneficial effects of "mental practice" on the physical performance (26, 28) may rely on the increment of cortical activity due to the close temporal association between motor rehearsal and actual performance. The effect may be accounted by a sort of neural recruiting that is made possible by overlapping of the cortical networks involved in motor output and in motor imagery (19). Finally, the fact that the motor pathways are globally activated during motor imagery represents a rationale for rehearsing effects observed in normal subjects during the motor learning (23, 27) and opens new possibilities for the rehabilitation of patients with motor impairments (9).

SUMMARY

The present fMRI study compares regional distribution of the cortical activity during the execution of unilateral hand movements (finger-to-thumb opposition) preceded or not by their motor simulation (S+E and E condition, respectively). The results show that, overall, the number and the spatial distribution of activated voxels are both increased in the S+E with respect to the E condition. The motor performance preceded by mental rehearsal is related to selective increase of the cortical activity. Among the motor areas that are found active during the simple motor execution a significant enhancement of functional activation during the S+E condition has been found only in the contralateral premotor area (PMA) and in the contra-and

ipsilateral primary motor regions (M1). The activity increase may be accounted by a sort of neural recruiting that is made possible by the overlapping of cortical networks involved in both motor output and motor imagery. The beneficial effects of "mental practice" on the physical performance may rely to the close temporal association between motor rehearsal and actual performance.

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