

Effector-dependent activity in the left dorsal premotor cortex in motor imagery

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Abstract

Although right- and left-hand motor imagery (MI) typically results in lateralized cortical activation patterns in various areas, such an effect has never been observed in the left premotor cortex (PMC). Using functional magnetic resonance imaging we tested whether the left PMC, which is supposed to be effector independent, i.e. it is activated irrespective of the hand used for MI, shows differential activation during right- and left-hand MI of ecologically valid everyday actions. Results showed that the left dorsal PMC was activated more strongly during right- than left-hand MI, and that the co-varying quality of imagination could not explain the observed effects. We conclude that the left dorsal PMC incorporates effector-dependent functionality and therefore is not fully generic for MI, as has been suggested before. Implications for clinical research are discussed.

Introduction

Motor imagery (MI), i.e. the internal rehearsal of a movement without overt physical movement (Crammond, 1997), is thought to drive a cortical network similar to motor execution (Jeannerod, 1994). Great overlap has not only been shown for the general activation pattern observed for MI and motor execution (Stephan *et al.*, 1995; Porro *et al.*, 1996; Lotze *et al.*, 1999), but also for more refined properties of the motor system, such as homuncular organization (Stippich *et al.*, 2002; Ehrsson *et al.*, 2003; Szameitat *et al.*, 2007) and lateralized organization (Michelon *et al.*, 2006), i.e. activation differences depending on the hand used. Such lateralized, effector-dependent activation during MI has been demonstrated for most regions of the motor system, including the primary motor cortex, supplementary motor area (SMA) and thalamus (Lotze *et al.*, 1999; Kutz-Buschbeck *et al.*, 2003; Michelon *et al.*, 2006; Stinear *et al.*, 2006b). An exception to this pattern is the premotor cortex (PMC). This area is consistently activated during MI tasks, but the evidence for lateralization is sparse and inconsistent. While one study (Kutz-Buschbeck *et al.*, 2003) observed that the right dorsal PMC is activated stronger when MI is performed with the contralateral (left) as compared to the ipsilateral (right) hand, all previous studies failed to observe an effect of performing hand in the left PMC. This observation has led to the proposition that the functional role of the left PMC is effector independent and primarily concerned with generic aspects of motor planning and control (Porro *et al.*, 2000; Hlustik *et al.*, 2002; Kutz-Buschbeck *et al.*, 2003).

However, natural actions of everyday life, such as writing or using a spoon, are often preferentially performed with the dominant hand. In addition, considerable performance decrements appear when such actions are conducted with the non-dominant hand (e.g. writing with the left vs right hand in right-handers). Such hand-dependent performance differences imply effector-dependent motor planning and control of such tasks. Because in right-handers motor planning and control is

primarily a function of the left PMC, we postulated that the left PMC shows effector-dependent activity when such tasks are used. To test this hypothesis we investigated in right-handers whether the left PMC shows differential activation when MI is performed with the left or right hand, respectively, by using kinaesthetic (first-person perspective) MI of ecologically valid everyday movements such as writing or drinking from a glass (Stinear *et al.*, 2006a; Szameitat *et al.*, 2007).

To assess the influence of effector dependency in motor performance on the left PMC we employed two conditions: one (DEP) consisting of effector-dependent actions, i.e. actions with a clear preference and advantage for one hand (e.g. writing); the other (INDEP) consisting of effector-independent actions that were performed comparably well with either hand (e.g. drinking from a glass).

To account for the potential confound that it may be harder to generate a vivid representation of non-dominant hand movements (Sabate *et al.*, 2004), which in turn could influence activation strength of cortical areas, the quality of imagination (QoI) was measured separately for each condition and hand.

Taken together, the aim of the current study was to investigate the influence of the performing hand in MI on the left PMC by using two different movement types and by controlling for possible differences in imagination quality.

Materials and methods

Participants

Seventeen right-handed (Oldfield, 1971) participants (six male) aged 19–31 (mean 22) years took part in the study. Prior to scanning, participants gave written informed consent according to the guidelines of the University of Surrey ethical review board.

Task and procedure

While lying in the functional magnetic resonance imaging (fMRI) scanner, participants viewed a projection screen via a mirror. We

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employed six conditions: MI of tasks with effector-dependent performance (DEP) with the left and right hand; MI of tasks with rather effector-independent performance (INDEP) with the left and right hand; a resting baseline (BASE); and MI of bimanual actions (not reported). Except for BASE, each condition was repeated seven times. The experiment was based on an fMRI block design and consisted of 35 cycles, each lasting 1 min. Each cycle embodied an instruction and preparation period (12 s), an imagination period (24 s) and the resting baseline BASE (24 s). Conditions were presented in a pseudorandomized order. The experiment was split into two functional runs, the first with 18 and the second with 17 cycles, respectively. Between the two runs a high-resolution anatomy was acquired, resulting in a break of 5–6 min for the participants.

As detailed in Szameitat *et al.* (2007), in the instruction period the movement to be imagined next was presented on a screen using black letters on a white background. In the following imagination period the screen turned black, and participants had to close their eyes and perform the imagination. Participants were cued to open the eyes again by the screen turning white, which, due to the intense change in luminance, was easy to recognize through the closed eye lids. Afterwards the resting baseline period was presented, during which participants had to fixate a cross on the screen. [Because participants had to open their eyes only during BASE, but not during the imagery conditions, this procedure may have introduced a confound. However, firstly this confound affects only the baseline comparisons LEFT–BASE and RIGHT–BASE, but not the direct comparison of LEFT and RIGHT. Secondly, this confound should result in higher activation during BASE, but not during imagery. Accordingly, the confound could only result in missed activations in the imagery conditions, but it cannot account for activations observed in the imagery conditions.] After the baseline period, the next cycle started by presenting the instruction and preparation period. Participants were instructed to imagine during the whole imagination period and, if the imagination of a movement finished earlier, to start over with the same movement until the imagination period finished. In addition, instructions emphasized an ‘action loaded’ imagination, i.e. participants were asked to perform the imagined movement with high frequency and engage intensely.

The INDEP movements were: (1) scratch your nose; (2) use a lightswitch (turn light on and off); (3) open door of cupboard (left/right door if performed with left/right hand, respectively); (4) drink glass of water placed on a table; (5) press a button (e.g. in a lift); (6) turn round knob (e.g. volume control at HiFi); (7) hang your coat on a hook. The DEP movements were: (1) write on a piece of paper using a pen; (2) brush your teeth; (3) use a computer mouse; (4) eat soup or cereals using a spoon; (5) throw something (in the trash bin/darts); (6) lock/unlock a door using a key; (7) shake hands.

To assess the vividness of the imagery, participants were asked to rate the goodness of imagination for each hand and condition (seven-point Likert scale). Prior to the scanning session participants further completed a questionnaire assessing the effector dependency of the tasks by asking the participants to judge how difficult the movements are to perform with the left and right hand, respectively, and with which hand they would preferentially perform the action (both employing a five-point Likert scale).

To control for overt movement during MI, participants held two force-sensitive grips in their hands (Hou *et al.*, 2005). Force data were sampled continuously throughout all conditions with a frequency of approximately 250 Hz. The grips are highly sensitive to force changes and are able to detect force variations not visible by visual inspection.

MRI procedure

Imaging was carried out at the Royal Holloway University London, UK, using a 3T scanner (Trio, Siemens, Erlangen, Germany) equipped with an array head coil. Participants were supine on the scanner bed, and cushions were used to reduce head motion. Thirty-six axial slices (192×192 mm FOV, 64×64 matrix, 4 mm thickness, no gap, interleaved slice acquisition) were acquired using an EPI sequence (TR 2 s, TE 30 ms, 90° flip angle). Two functional runs, the first with 540 and the second with 510 volumes were administered, with each volume sampling all 36 slices. In the same session, high-resolution whole-brain images were acquired from each participant using a T1-weighted MPRAGE sequence ($1 \times 1 \times 1$ mm voxel size).

Data analysis

The data were analysed using SPM2 (<http://www.fil.ion.ucl.ac.uk/spm/software/spm2/>). First, the origin of the anatomical and functional images was manually set to the anterior commissure and all images were reoriented. To correct for movements, all functional volumes were spatially realigned to the first functional volume, and signal changes due to head motion and magnetic field inhomogeneities were corrected (Andersson *et al.*, 2001). Anatomical and functional images were normalized into the MNI space, and functional data were spatially smoothed using a Gaussian kernel with a FWHM of 8 mm. Normalization and registration success was validated by visual inspection.

Statistical analysis was based on a voxel-wise least squares estimation using the general linear model for serially autocorrelated observations (Friston *et al.*, 1995). A temporal high-pass filter with a cutoff frequency of $1/300$ Hz was applied. Individual contrast maps were calculated for the baseline comparisons RIGHT–BASE [i.e. $(R_{\text{Dep}} + R_{\text{Indep}})/2 - \text{BASE}$] and LEFT–BASE [i.e. $(L_{\text{Dep}} + L_{\text{Indep}})/2 - \text{BASE}$], respectively, and for the direct comparisons RIGHT–LEFT [i.e. $(R_{\text{Dep}} + R_{\text{Indep}}) - (L_{\text{Dep}} + L_{\text{Indep}})$] and LEFT–RIGHT [i.e. $(L_{\text{Dep}} + L_{\text{Indep}}) - (R_{\text{Dep}} + R_{\text{Indep}})$]. The second-level analysis was based on random-effects paired *t*-tests. The resulting statistical parametric *t*-map was thresholded at $t_{16} > 3.69$ (voxel-level $P < 0.001$ uncorrected) with an extent threshold of 50 voxel for display purposes. To account for multiple comparisons we considered only activation clusters that surpassed a corrected cluster-level significance of $P < 0.05$. Stereotaxic coordinates are reported using the space of Talairach & Tournoux (1988). Anatomical locations and Brodmann’s areas were determined using the SPM Anatomy Toolbox (Eickhoff *et al.*, 2005), and the atlas of Talairach & Tournoux (1988).

To test in detail for the activity in the left PMC we conducted a region of interest (ROI) analysis. For this, clusters of activation from the group analysis RIGHT vs LEFT were defined as ROI, and the percent signal change (PSC) was extracted for each ROI, participant and condition using MarsBar (Brett *et al.*, 2002). The resulting data were examined using paired-sample *t*-tests (one-tailed, as we expected the left PMC to be activated more strongly by right-hand MI than by left-hand MI).

Results

Questionnaires and grip force

Participants assigned higher effector dependency to DEP than INDEP movements. While both DEP and INDEP were preferentially performed with the right hand (INDEP: $t_{16} = 6.527$, $P < 0.001$; DEP: $t_{16} = 31.082$, $P < 0.001$), this preference was more pronounced in DEP than in INDEP ($t_{16} = 11.062$, $P < 0.001$). In addition, both tasks

were judged to be more difficult to perform with the left than the right hand (DEP L vs R: $t_{16} = 20.3$, $P < 0.001$; INDEP L vs R: $t_{16} = 4.6$, $P < 0.001$), and again this difference was more pronounced in DEP than in INDEP (interaction hand[R/L] \times task[INDEP/DEP] $F_{1,16} = 630.00$, $P < 0.001$).

Force data recorded during the whole scanning session were averaged for each condition and participant. We observed no significant differences between MI conditions either for the left hand, the right hand or the average of both hands (all $t_{16} < 1.795$, all $P > 0.05$).

Baseline comparisons (LEFT-BASE and RIGHT-BASE)

MI with the left and right hands, each individually compared with baseline (averaged across DEP and INDEP), resulted in a highly comparable activation pattern (Fig. 1, Table 1). Most notably, large parts of the premotor system were activated, including the bilateral SMA, bilateral ventral and dorsal PMCs, and the right inferior frontal gyrus. In addition, the left middle frontal gyrus, and bilateral postcentral and temporal areas were involved in MI. Cerebellar activation, which is frequently observed during MI, was evident bilaterally in both comparisons only at a lowered uncorrected threshold (peak in LEFT-BASE at $-4x$, $-53y$, $-4z$, $t_{16} = 4.28$, $P(\text{voxel-level uncorrected}) \leq 0.001$, volume 113 voxel; peak in RIGHT-BASE at $-8x$, $-51y$, $-11z$, $t_{16} = 2.95$, $P(\text{voxel-level uncorrected}) \leq 0.003$, volume 37 voxel).

It is particularly noteworthy that the activation peaks in the individual comparisons (RIGHT-BASE and LEFT-BASE) were highly congruent, and usually differed no more than 4 mm with a peak incongruency of only 7 mm. This indicates that MI with the left and right hand was subserved by a virtually identical network of cortical areas.

Both the direct comparison of DEP and INDEP as well as the interaction between movement type [DEP/INDEP] and hand used in MI [L/R] did not reveal any significant activation patterns, with the only exception of scattered precuneus activation in INDEP-DEP. [The questionnaire data indicate that the DEP movements might be more difficult to perform overtly than the INDEP movements, and one might wonder why such a potential difficulty difference is not evident in the fMRI results. Although the reasons for the absence of any significant effects are not clear, at least two possibilities are conceivable. Firstly, even the most difficult condition (DEP with left hand) was characterized only as being between '3/moderate' and '4/difficult' to perform (mean 3.56 of the 1-5 scale), so that the relative difference between the conditions may have been too small to result in measurable effects. Secondly, although the DEP movements have been characterized as being more difficult to perform, not all DEP movements are more complex in nature (e.g. shake hands, use mouse, unlock door). Thus, if not difficulty *per se* but movement complexity (e.g. in terms of timing and trajectory) is the crucial factor, no differences would be expected.]

Right- vs left-hand MI

We predicted differential activation of the left PMC depending on the hand used in MI. This hypothesis was confirmed by the direct comparison of MI with left and right hand (i.e. RIGHT-LEFT), averaged across DEP and INDEP, which showed that the left dorsal PMC was activated more strongly by right-hand MI than by left-hand MI ($-30x$, $-9y$, $61z$, $t_{16} = 5.54$, $P(\text{cluster-level corr}) < 0.01$; cluster volume 361 voxels). This activation (Fig. 2A) was located in Brodmann area 6 (Eickhoff *et al.*, 2005) of the left dorsal precentral gyrus. No other activation clusters were evident or reached significance in this comparison, and no area showed stronger activation for left- than right-hand MI (i.e. no activations in contrast LEFT-RIGHT).

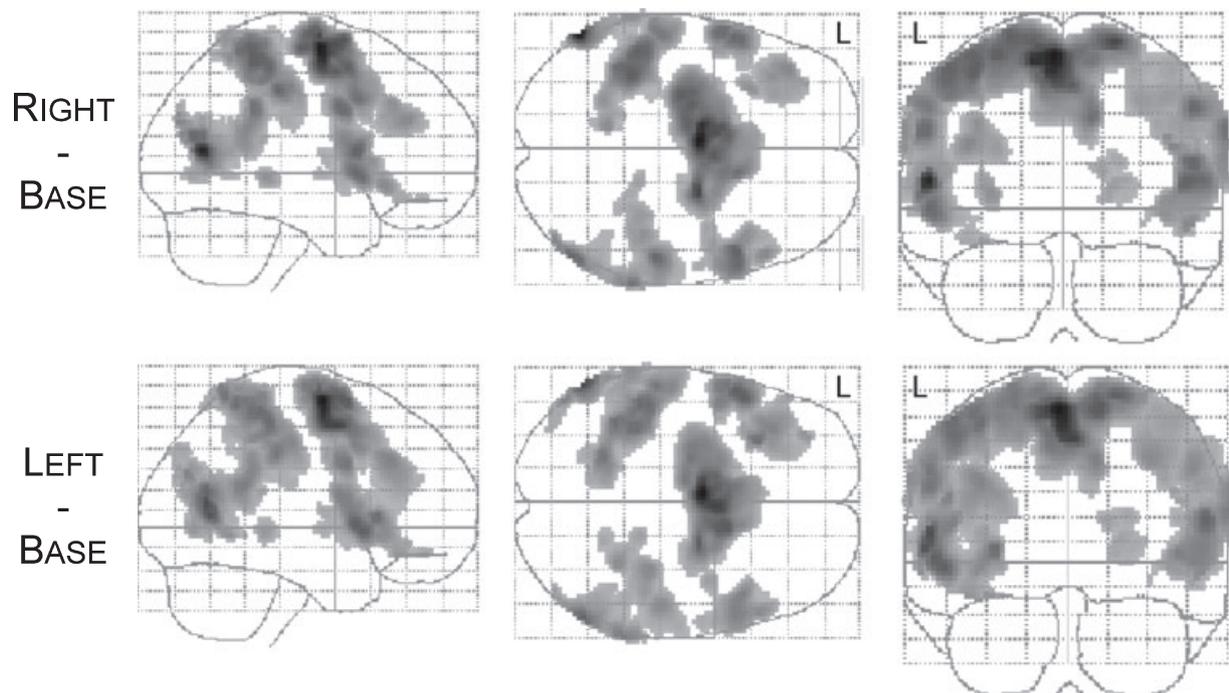


FIG. 1. Cortical activations of the contrasts RIGHT-BASE (top row) and LEFT-BASE (bottom row). SPMs were thresholded at $t > 3.69$, $P < 0.001$ (uncorrected), extent threshold 50 voxels.

TABLE 1. Anatomical locations, Brodmann's areas (in brackets), stereotaxic coordinates (Talairach & Tournoux, 1988), and *t*-scores of the individual baseline comparisons LEFT-BASE and RIGHT-BASE (both averaged across DEP and INDEP)

Anatomical location	RIGHT-BASE						LEFT-BASE					
	Coordinates			<i>t</i> -value	Volume	<i>D</i>	Coordinates			<i>t</i> -value	Volume	
	<i>x</i>	<i>y</i>	<i>z</i>				<i>x</i>	<i>y</i>	<i>z</i>			
L middle frontal G (9/8/46)	-40	38	24	5.9	761*	-	-	a	-	4.83	-	
L middle frontal G (9)	-36	31	30	5.44	-	2	-36	29	30	6.63	b	
L middle frontal G (9)	-28	30	22	4.93	-	-	-	a	-	4.71	-	
L SMA (6)	-4	-5	59	12	7834*	2	-4	-3	59	13.41	4642*	
L SMA (6)	-12	-3	57	10.8	-	6	-12	3	57	8.7	-	
R SMA (6)	4	2	48	8.2	-	2	2	2	48	10.7	-	
R SMA (6)	12	9	57	6.98	-	3	12	7	59	9.13	-	
L rolandic operculum (44)	-55	10	0	7.51	992*	1	-55	10	1	8.8	2961*	
L precentral G (6/44)	-57	5	29	7.37	-	2	-57	7	29	7.43	-	
L rolandic operculum (44)	-53	5	13	5.31	-	2	-51	5	13	6.86	-	
L insula	-30	18	5	5.43	87* ^{ns}	4	-30	22	4	7.9	-	
R IFG (pars Operc) (44)	51	10	11	7.86	1528*	7	55	10	5	6.8	1366*	
R IFG (pars Orbitalis) (45)	53	23	-6	5.93	-	3	55	21	-4	6.23	-	
R IFG (pars Operc) (44)	46	14	3	5.69	-	0	46	14	3	6.74	-	
L postcentral G (2/1)	-48	-34	55	8.01	c	2	-50	-34	55	8.05	2954*	
L postcentral G (2)	-38	-38	55	8.19	c	0	-38	-38	55	7.85	-	
L superior parietal lobe (7)	-	a	-	7.22	c	-	-40	-46	59	7.82	-	
R middle temporal G (39)	53	-69	20	7.66	2341*	7	57	-63	20	8.49	1234*	
R inferior parietal lobe (40)	67	-39	33	7.08	-	3	67	-39	30	6.46	-	
R superior temporal G (22)	67	-44	22	6.03	-	0	67	-44	22	7.06	-	
R SMG/postcentr G (2/40)	53	-27	40	7.6	-	3	51	-25	38	6.26	1528*	
R postcentral G (2/3a)	34	-35	44	5.01	-	4	34	-31	42	6.25	-	
R superior parietal lobe (7)	30	-43	67	4.09	-	2	30	-45	67	6.08	-	
L middle temporal G (39)	-55	-65	14	11.2	c	3	-57	-63	14	9.87	487*	
L inf par lobe/angular G (39)	-	a	-	ns	-	-	-50	-72	29	6.65	-	
L middle temporal G (37)	-	a	-	4.38	c	-	-61	-58	3	6	-	

*Absolute peaks are indicated in the Volume columns, the other peaks are all local. *D* denotes the Euclidian distance between the peaks of the two contrasts in mm.

^aBecause there was no local or absolute activation peak in the vicinity, the *t*-value at the location of the respective other contrast is reported. For instance, in the comparison LEFT-BASE, the *t*-value at the location -40, 38, 24 is 4.83. This demonstrates virtually always supra-threshold activation despite the absence of peaks.

^bPart of the cluster at -4, -3, 59; ^cpart of the cluster at -40, 38, 24. ^{ns}Note that the peak in the left insula is not significant for RIGHT-BASE when corrected for multiple comparisons on the cluster level ($P = 0.301$). Abbreviations: G, gyrus; IFG, inferior frontal gyrus; inf par lobe, inferior parietal lobe; pars Operc, pars opercularis; SMA, supplementary motor area; SMG, supramarginal gyrus; Vol, volume in voxel ($2 \times 2 \times 2$ mm).

The ROI analysis of the left PMC cluster (Fig. 2B top) revealed significant activation for all conditions (one-sample *t*-tests vs 0: all $t_{16} > 5.908$, all $P < 0.001$). In addition, left-hand MI resulted in smaller PSC in both conditions, DEP ($t_{16} = 3.143$, $P < 0.01$) and INDEP ($t_{16} = 1.746$, $P < 0.05$), whereby the effect size did not differ significantly between DEP and INDEP (interaction hand[R/L] \times task[DEP/INDEP] $F_{1,16} = 0.297$, $P = 0.593$). Thus, we were able to demonstrate that left dorsal PMC activity is modulated by the hand used in MI and that this modulation is unaffected by effector-dependent performance differences as implied by the two different movement types.

In MI QoI may differ between right- and left-hand MI, constituting a potentially confounding factor for the present analysis. Indeed, outcomes of the questionnaire showed that QoI was lower for left-hand MI than for right-hand MI (Fig. 2B bottom; paired-sample *t*-tests INDEP: $t_{16} = 3.559$, $P < 0.01$; DEP: $t_{16} = 4.518$, $P < 0.001$). To test whether this QoI difference could have caused the observed activation differences in the left PMC, a correlation analysis was performed to determine the association of QoI intensity and PSC activation level for left- and right-hand MI. Results showed that correlations between the effect of the used hand on QoI and PSC were far from significant for the whole sample (Fig. 2C, left column; highest absolute Pearson's $r = 0.299$, most significant $P = 0.243$) as well as after exclusion of two potential outliers (Fig. 2C, right column; highest absolute Pearson's $r = 0.070$, most significant $P = 0.803$). This absence of

any significant correlation demonstrates that it is highly unlikely that differences in QoI can account for the differences in the activation pattern observed in the SPM and ROI analyses.

Discussion

In this study, MI of right-hand actions resulted in stronger activation of the left dorsal PMC than MI of left-hand actions. This result was evident for rather effector-independent actions (e.g. drinking from a glass) as well as for highly effector-dependent actions (e.g. writing). Notably, the data can not be explained by co-varying differences in the QoI, as the latter was uncorrelated to the PSC modulations. Thus, our findings demonstrate that the left dorsal PMC implements effector-dependent, i.e. hand-specific, functionality and therefore is not fully generic for MI of both hands.

The effector dependency of the left dorsal PMC implies a functional specialization of the left dorsal PMC for right-hand actions. This specialization is congruent with the fact that the employed movements are preferentially performed with the dominant right hand. In addition, frequent and behaviourally relevant performance, as is the case for everyday movements, has been associated with enlarged representations of the neural networks controlling the respective effectors or movements (Karni *et al.*, 1995; Hlustik *et al.*, 2004; Baumann *et al.*, 2007). We therefore propose that the functional specialization of the left dorsal PMC for right-hand actions in right-hand dominant participants

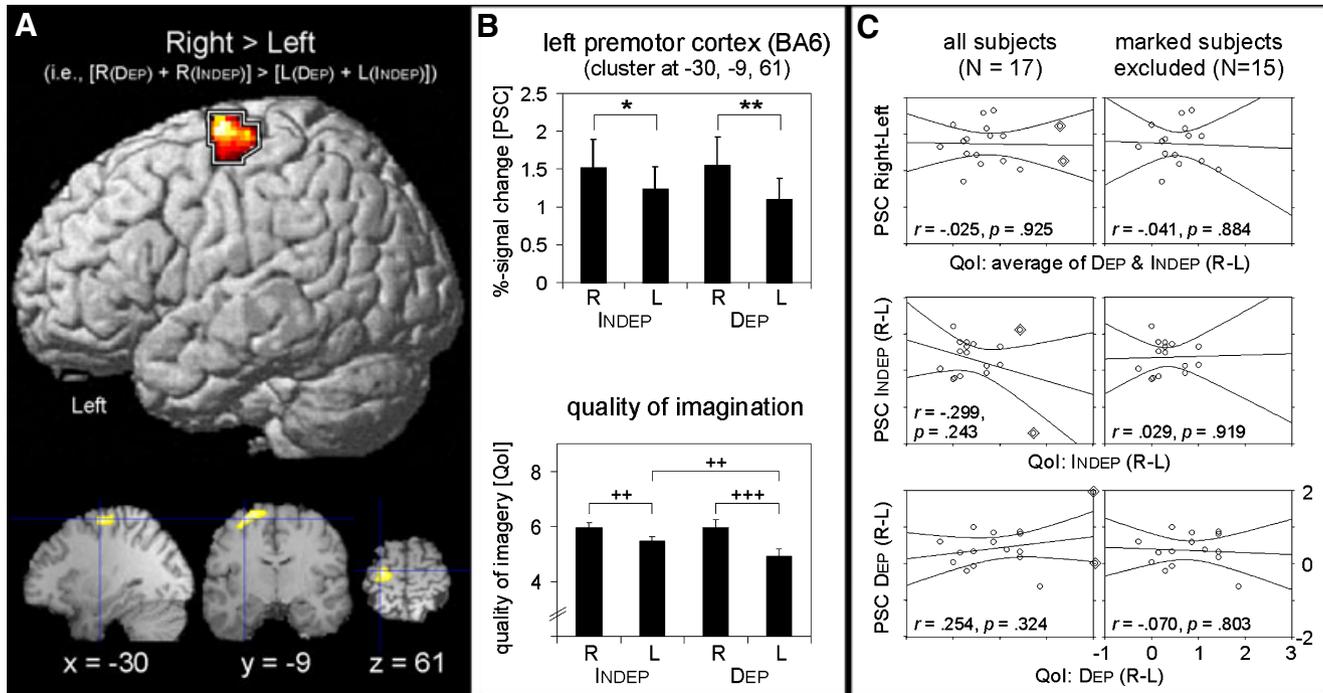


FIG. 2. (A) Cortical areas more strongly activated by right- than by left-hand MI. For clarity, the activated area is bordered in the top panel. Coordinates in Talairach space (Talairach & Tournoux, 1988). (B) ROI analysis of the activation cluster depicted in (A) (top) and quality of imagination (QoI) data (bottom). Error bars denote SEM. (C) Correlations between percent signal change (PSC) differences (right–left) and QoI differences (right–left). Top: PSC derived directly from the contrast depicted in Fig. 1, i.e. RIGHT–LEFT; QoI mean of INDEP and DEP. Middle/bottom: PSC and QoI differences for the INDEP/DEP condition, respectively. Left column all 17 participants, right column two potential outlier participants (marked by diamonds) excluded. Insets: Pearson's correlation coefficient r and its associated significance P . Linear regression lines with 95% confidence interval included. * $P < 0.05$ (one-tailed), ** $P < 0.01$ (one-tailed), +++ $P < 0.001$ (two-tailed).

is associated with the frequent use of these actions with the dominant hand, and henceforth represents a use-related adaptation of cortical circuitry. We further suggest that differences in neural representations subserving motor actions may well explain why previous studies found no effector-dependent effects in the left PMC. These experiments asked participants to imagine actions that are infrequently used in everyday life or are rather simple and arbitrary, such as finger tapping (Kuitz-Buschbeck *et al.*, 2003), fist making (Lotze *et al.*, 1999) or rotational hand movement (Michelon *et al.*, 2006). It is unlikely that effector-specific neural representations for this type of task have been developed. The same argument can account for the absence of effector-dependent effects for left-hand MI, e.g. in the right PMC. Although the presently used tasks show differences in hand preference, they are still preferentially performed with the dominant (right) hand, so that it is unlikely that effector-specific mechanisms have been developed for the left-hand performance of these tasks. Identification of effector-dependent representations therefore seems to depend crucially on the type of action participants are asked to imagine.

In line with the previous suggestion that the left PMC incorporates effector-independent functionality (Kuitz-Buschbeck *et al.*, 2003), we found that the left PMC was activated during MI of either hand. The important new finding is that the left PMC is not solely effector independent, but that effector-dependent functionality can be observed at the same time as well. This may be caused either by a single mechanism that shows effector-independent properties in some circumstances (such as plain tasks) and effector-dependent properties in others (such as everyday tasks), or by two mechanisms (one effector-dependent and one -independent) that are spatially intermingled or very close to each other. However, the present data cannot differentiate between these two alternatives.

While the present data clearly demonstrate the effector dependency of the left dorsal PMC, they also provide evidence for effector-independent representations in other areas. In general, left- and right-hand MI recruited a virtually identical network of cortical areas. Thus, most areas involved in MI in general can be considered as effector independent. While this may be straightforward for non-motor areas such as temporal cortices, it is interesting to note that there are effector-independent motor cortices, such as the bilateral ventral PMCs or the SMA, as well (cf. Rijntjes *et al.*, 1999; Kuitz-Buschbeck *et al.*, 2003). This corroborates the above-mentioned suggestion that the PMC incorporates both effector-dependent and effector-independent mechanisms.

The present study assessed for the first time hand-dependent differences in QoI objectively by using a questionnaire. This enabled us to statistically test whether the observed differences in left dorsal PMC activation were related to differences in QoI. Although in our study the observed differences in QoI did not correlate with activation differences in the left dorsal PMC, it cannot be ruled out that QoI might have an effect on other MI-related areas such as the SMA or the primary motor cortex. Accordingly, we suggest incorporating QoI measures in future studies of MI separately for each condition in order to ensure that observed differences in brain activation are not caused by differences in QoI.

The natural everyday actions used for MI in the present study have potential advantages in clinical research with neurological patients suffering from very low residual motor abilities. In such patients, MI is often used as a means to investigate the motor system or as an approach to initiate recovery (Sharma *et al.*, 2006). However, such patients are unable to practice the movement overtly before MI, which may result in less accurate and less vivid MI. A possible solution would be to use

very easy tasks that do not need practice. However, Kuhtz-Buschbeck *et al.* (2003) found a lateralization effect of performing hand in MI only in a rather complex but not in a simple task. This indicates that such simple tasks may not optimally engage the motor system, which in turn may result in a less optimal rehabilitation success. Another solution is to use everyday actions, as these actions can easily be modulated in their complexity and are so familiar to patients that it should be possible for them to generate a vivid mental representation without prior practice. While we already showed in a previous study (Szameitat *et al.*, 2007) that MI of everyday actions modulates activity in somatosensory cortices according to the homuncular organization, the present study extends this finding and shows that lateralization effects can be observed as well. This demonstrates that clinical research and application might benefit from using MI of natural everyday actions instead of simpler tasks.

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Abbreviations

fMRI, functional magnetic resonance imaging; MI, motor imagery; PMC, premotor cortex; PSC, percent signal change; QoI, quality of imagination; ROI, region of interest; SMA, supplementary motor area.

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