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Lange, F.P. de; Roelofs, K.; Toni, I.

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Increased self-monitoring during imagined movements in conversion paralysis

Floris P. de Lange [a,*,1], Karin Roelofs [b,1], Ivan Toni [a,c]

[a] *F.C. Donders Centre for Cognitive Neuroimaging, Radboud University Nijmegen, Kapittelweg 29, 6500 HB Nijmegen, The Netherlands*
[b] *Department of Clinical, Health and Neuropsychology, University of Leiden, The Netherlands*
[c] *Nijmegen Institute for Cognition and Information, Radboud University Nijmegen, The Netherlands*

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Abstract

Conversion paralysis is characterized by a loss of voluntary motor functioning without an organic cause. Despite its prevalence among neurological outpatients, little is known about the neurobiological basis of this motor dysfunction. We have examined whether the motor dysfunction in conversion paralysis can be linked to inhibition of the motor system, or rather to enhanced self-monitoring during motor behavior.

We measured behavioral and cerebral responses (with fMRI) in eight conversion paralysis patients with a lateralized paresis of the arm as they were engaged in imagined actions of the affected and unaffected hand. We used a within-subjects design to compare cerebral activity during imagined movements of the affected and the unaffected hand.

Motor imagery of the affected hand and the unaffected hand recruited comparable cerebral resources in the motor system, and generated equal behavioral performance.

However, motor imagery of the affected limb recruited additional cerebral resources in the ventromedial prefrontal cortex and superior temporal cortex. These activation differences were caused by a failure to de-activate these regions during movement imagery of the affected hand. These findings lend support to the hypothesis that conversion paralysis is associated with heightened self-monitoring during actions with the affected arm.

Keywords: fMRI; Mental rotation; Motor imagery; Conversion disorder; Medial prefrontal cortex; Default mode network

1. Introduction

Conversion paralysis (CP) is a mental disorder characterized by loss of voluntary motor functioning. Although the symptoms may suggest a neuropathological condition, they cannot be adequately explained by known neurological or other organic disorders (American Psychiatric Association, 1994). Moreover, there is an exacerbation of symptoms at times of psychological stress, which suggest that psychological mechanisms play a role.

Conversion disorder and related disorders are common in clinical practice: about one-third of new neurological outpatients exhibit medically unexplained symptoms (Carson et al., 2000; Stone, Carson, & Sharpe, 2005a). Despite the high prevalence and the long history of speculations as to the cause of CP (Halligan, Bass, & Marshall, 2001; Vuilleumier, 2005), the exact nature of CP is still not well understood. Only recently, a few studies have tried to determine objective neural correlates of functional mechanisms that, in the absence of a structural brain lesion, may be able to explain CP symptomatology. The first study to investigate the functional anatomy of conversion paralysis was by Marshall, Halligan, Fink, Wade, and Frackowiak (1997). Using positron emission tomography (PET), the authors recorded brain activity when a patient with unilateral CP tried to move either her affected or her unaffected leg. When attempting to move the unaffected (right) leg, there was a normal pattern of cerebral activity, including activation in the contralateral primary motor cortex (M1). However, when attempting to move the affected (left) leg, there was no activation in the contralateral M1, but there was a relative increase in activation of the right anterior cingulate cortex (ACC) and the ventromedial part of the prefrontal cortex (vmPFC). These results were interpreted as

* Corresponding author. Tel.: +31 24 36 10887; fax: +31 24 36 10652.
E-mail address: floris.delange@fcdonders.ru.nl (F.P. de Lange).
[1] Authors contributed equally to this work.

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suggesting that the loss of voluntary movements observed in CP is caused by increased response inhibition mediated by ACC and vmPFC. Similar results were obtained in a related study, in which hypnosis was used to induce paralysis of the leg in a healthy subject (Halligan, Athwal, Oakley, & Frackowiak, 2000). When the hypnotized participant tried to move his "affected" leg, ACC and vmPFC showed increased activity, suggesting that similar mechanisms support hypnotically induced paralysis and CP (Halligan et al., 2000). In contrast, Spence, Crimlisk, Cope, Ron, and Grasby (2000) observed that when CP patients moved their paretic limb, there was a de-activation in their dorsolateral prefrontal cortex (dlPFC), as compared to healthy control subjects. Finally, Burgmer et al. (2006) did not find any differences in prefrontal or motor cortex activity between CP patients and healthy controls during execution of hand movements. Although these conflicting results may be partly due to the limited sample size ($N = 1$–4), and the type of comparisons carried out (*within*-subjects versus *between*-subjects), a more fundamental issue may relate to the nature of the tasks employed. Namely, in these studies, patients were asked to carry out a task ("move/try to move your affected limb") that they could not appropriately perform due to their condition. Accordingly, it is conceivable that these results reveal cerebral effects related to the cognitive consequences of a failed movement (like altered effort, motivation, or error processing), rather than a proximal cause of CP. For instance, the increased ACC activity (Halligan et al., 2000; Marshall et al., 1997) may reflect enhanced monitoring triggered by movement failure or by conflicting action tendencies (Vuilleumier et al., 2001). This possibility is supported by our recent finding of increased action monitoring in the ACC of six unilateral CP patients during generation of movements with the affected limb (Roelofs, de Bruijn, & Van Galen, 2006).

To overcome these interpretational limitations, Vuilleumier et al. (2001) assessed brain responsiveness to sensory stimulation in CP patients suffering from unilateral sensorimotor loss. In an elegant design, both the affected and the unaffected limb were stimulated, and the cerebral responses of CP patients were measured at two time points: first, when conversion symptoms were present, and several weeks later, when the symptoms were resolved. Patients had decreased activity in the basal ganglia and thalamus contralateral to the affected limb during sensory stimulation of the affected limb compared to stimulation of the unaffected limb. This decrease resolved after recovery of conversion symptoms, suggesting that differences in sensory processing may play an important role in the pathophysiology of CP. However, it has yet to be investigated how these *sensory* deficits relate to the core feature of CP, namely the disturbance of volitional motor processes. Finally, a recent study explored whether CP is associated with abnormal brain activity during observation of hand movements (Burgmer et al., 2006). This study showed that compared to healthy controls, CP patients had reduced M1 activity during observation of hand movements, specifically for the affected hand. However, despite the known behavioral and neural correspondences between action observation and action execution (Grezes & Decety, 2001; Hamilton, Wolpert, & Frith, 2004), it is not trivial to link this finding to the main symptomatology of CP (limb paralysis), given that action observation does not entail an active volitional motor simulation. In the present study, we aimed to examine volitional action simulation while controlling for processes associated with actual motor execution like altered sensory feedback or enhanced monitoring of failed movements. We addressed this issue by using a motor imagery paradigm.

Using motor imagery to study the generation and preparation of actions is supported by a wealth of evidence showing that imagined and executed movements overlap in terms of time course (Parsons, 1987, 1994; Sekiyama, 1982), autonomic responses (Decety, Jeannerod, Germain, & Pastene, 1991), and neural architecture (de Lange, Hagoort, & Toni, 2005; Jeannerod, 1994; Parsons, Gabrieli, Phelps, & Gazzaniga, 1998). Accordingly, previous behavioral studies have used motor imagery tasks to reveal impairments in motoric simulations of the affected limb in patients with CP (Maruff & Velakoulis, 2000; Roelofs et al., 2001). Here we used a well-known motor imagery task: the hand-laterality judgment task. In this mental rotation paradigm, subjects have to judge the laterality of rotated images of left and right hands. Many studies have showed that subjects solve this task by mentally moving their own hand to match the orientation of the visually presented stimulus (Parsons, 1987, 1994). This approach allowed us to compare cerebral activity (using fMRI) evoked by motor imagery of the affected and the unaffected hand, while quantifying imagery performance. We hypothesized that, if CP entails an inhibition of the movement plan, activity should be increased in the cingulate and prefrontal cortex during motor imagery of the affected hand, while there should be a reduction of preparatory activity in motor-related structures (Burgmer et al., 2006; Marshall et al., 1997). Alternatively, if CP entails heightened action monitoring triggered by movement failure or by conflicting action tendencies (Roelofs et al., 2006; Vuilleumier et al., 2001), we expected the prefrontal hyperactivity to be accompanied by normal or even greater activity in the motor system, due to the increased effort in forming a motor plan.

2. Materials and methods

2.1. Participants

We studied eight patients (mean age of 34.6 years, range 18–56, S.D. = 13.2) diagnosed with conversion disorder according to the DSM-IV criteria (American Psychiatric Association, 1994) and showing a full or partial paralysis lateralized to one arm as a major symptom. A criterion for inclusion was a strictly unilateral loss of motor function, clearly related to psychogenic factors and in the absence of any neurological disease (American Psychiatric Association, 1994). After referral by a neurologist, a trained psychologist assessed whether the patients met the DSM-IV criteria for conversion disorder and checked for other axis-I diagnoses using the Structured Clinical Interview for DSM-IV Axis-I Disorders [SCID-1/p (First, Spitzer, Gibbon, & Williams, 1996)]. Exclusion criteria were symptoms involving pseudo-epileptic insults, tremors, sudden movements and deteriorated speech or vision. Four patients showed conversion paresis to the right arm and the other four patients to the left arm. Lateralization of the paresis was examined by measuring maximal contraction force. Isometric force measurements of maximum voluntary contractions (MVC) of the left and right hand were obtained with a Biometrics hand dynamometer (Almere, The Netherlands). Force measures confirmed that the maximal force that could be exerted with the affected arm was considerably lower than with the unaffected hand in all patients ($t_{(7)} = 5.26$, $p = 0.001$). One patient used antidepressant medication (Sertraline,

Table 1
Demographical characteristics of the participants

Patient	Age	Gender	Affected hand	Dominant hand	Duration of complaints[a]	MVC[b] affected	MVC[b] unaffected	History of traumatic events	Events preceding symptom onset	Axis-I comorbidity (SCID-I)
1	48	Female	Right	Right	36	100.8	139.4	Emotional and sexual abuse	Family conflict	Depressive disorder in remission
2	34	Male	Left	Right	35	157.2	219.4	–	Suicide attempt by sibling	–
3	43	Female	Right	Right	3	8.9	106.8	Sexual and physical abuse	Family conflict	–
4	23	Female	Right	Right	41	59.3	139.4	–	Car accident	–
5	27	Male	Left	Left	26	172.0	261.0	–	Work accident	–
6	56	Male	Left	Left	14	53.4	231.3	Involved in deadly accident	Death of partner, loss of house	–
7	28	Female	Right	Right	19	86.0	127.5	–	School exam	–
8	18	Female	Left	Right	3	4.4	154.2	Emotional abuse; left arm fracture	Panic attack, change of living situation	Anxiety disorder n.o.s.

[a] In months.
[b] Maximum voluntary contraction in Newtons, measured with a hand dynamometer.

50 mg/day). None of the patients used anti-convulsants, benzo-diazepines, or other substances that are known to have an effect on cerebral blood flow. Table 1 shows demographic information of all the participants. The study was approved by the local medical ethical committee and all patients gave their informed consent before participation.

2.2. Task

We used a well-known motor imagery task, in which the participants have to judge the laterality of the visually presented rotated hand stimulus (Parsons, 1987). We used line drawings of left and right hands, in different orientations varying from 0° to 180° in 45° steps (both clockwise and counter-clockwise). We defined the 0° orientation of the hand as the orientation in which the fingers are vertical and pointing upwards. The hand could be shown in either palmar or dorsal orientation. The stimuli were serially presented to the patients in a random order. For each trial, the hand stimulus was presented centrally on the screen, and patients were instructed to judge as fast and as accurately as possible whether the stimulus constituted a left or a right hand. When the patient provided his/her response, the stimulus was replaced with a fixation cross, which stayed on until the start of the next trial (inter-trial interval: 1.5–2.5 s). The experiment consisted of 160 trials of motor imagery. After a series of 10 motor imagery trials, a rest period of 10 s was introduced to sample baseline activity. During this rest period, patients were instructed to look at the fixation cross.

Patients responded by pressing one of two buttons attached to their left or right big toe. The patients' left and right feet were firmly attached to a button box, and reaction times and error rates were measured for subsequent behavioral analysis. The stimuli were presented using Presentation software (Neurobehavioral systems, Albany, USA), and they were projected onto a screen at the back of the scanner and seen through a mirror above the patients' heads.

2.3. Behavioral analysis

Mean response times (RTs) were calculated for each level of the two experimental factors (hand, rotation). A two-way (2 × 5) repeated-measures ANOVA was carried out to examine the effects of hand (affected, unaffected) and rotation (0–180° in 45° steps) on RT. Differences in error rate between the affected and the unaffected hand were investigated using a paired-samples *T*-test. Alpha-level was set at $P < 0.05$.

2.4. MRI acquisition and analysis

Functional images were acquired on a Siemens (Erlangen, Germany) 1.5 T MRI system equipped with echo planar imaging (EPI) capabilities using the standard head coil for radio frequency transmission and signal reception. Functional images were acquired using a gradient EPI-sequence (TE/TR = 40/2540 ms; 32 axial slices, voxel size = 3.5 mm; FOV = 224 mm). On average, the duration of the experiment was 23 min in which 547 scans were acquired. High-resolution anatomical images were acquired using a MP-RAGE sequence (TE/TR = 3.93/2250 ms; voxel size = 1.0 mm, 176 sagittal slices; FOV = 256 mm). Preprocessing of the functional data and calculation of the contrast images for statistical analysis was done with SPM5 (http://www.fil.ion.ucl.ac.uk/spm). First, functional images were realigned, slice-time corrected, normalized to a common stereotactic space (MNI: Montreal Neurological Institute, Canada) and smoothed with a 10 mm FWHM Gaussian kernel. By jittering trial onsets with respect to image acquisition and randomizing stimulus rotations, our experimental design allowed for an event-related analysis of the fMRI time series. For each patient, we modeled activity evoked by motor imagery (two levels: affected versus unaffected), as well as the increase in activity with increasing biomechanical complexity during motor imagery. The laterality of the affected hand was pooled across subjects. We based the biomechanical complexity of the movement on the average behavioral response for each level of rotation (five levels: from 0° to 180° in 45° steps). In other words, we parameterized the fMRI rotation-related increase as a non-linear process with the same shape as the RTs. Incorrect responses were separately included in the model. To remove any artifactual signal changes due to head motion, we included six parameters describing the head-movements (three translations, three rotations) as confounds in the model. Linear contrasts pertaining to the main effects of the factorial design constituted the data for the second-stage analysis, which treated participants as a random factor. In this second-stage analysis, we tested the following contrasts: (1) common increases in activity with rotation (as parameterized by the regressors describing the rotation-related increase) versus baseline; (2) rotation-related differences between the affected and the unaffected hand; (3) overall activity differences between the affected and the unaffected hand; and (4) overall activity differences between the left and the right hand. Because the relatively small sample size could potentially violate the normality assumption of the data, we carried out the second-stage analysis in a non-parametric framework (Holmes, Blair, Watson, & Ford, 1996) using SnPM3 (http://www.sph.umich.edu/nistat/SnPM). We employed a locally pooled variance estimate, with a Gaussian kernel of 10 mm FWHM (Nichols & Holmes, 2002). To optimize statistical sensitivity for both spatially extended clusters and high intensity signals, we used a combined threshold on the basis of voxel-intensity and cluster size (Hayasaka & Nichols, 2004), using a pseudo-*T* value of 2.8 (corresponding to $p \approx 0.01$) for identification of supra-threshold clusters. Note that this threshold is only used to define clusters, and does not denote the threshold for significance of activations. All reported clusters survive whole-brain correction for multiple comparisons, using a statistical threshold of $p < 0.05$. Anatomical details of activated clusters were obtained by superimposing the SPMs on the structural images of the patients.

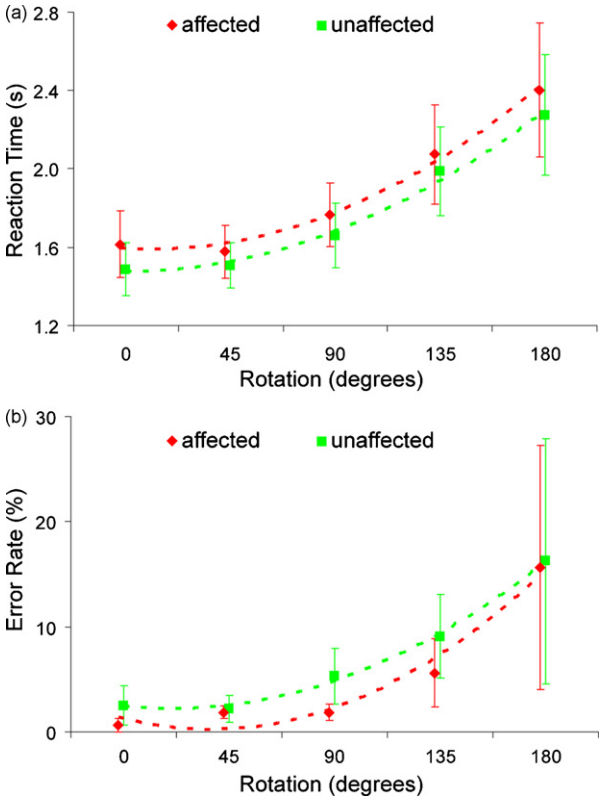

Fig. 1. Behavioral data. (a) Reaction times (mean ± S.E.M.) for laterality judgments of the affected hand (in red) and the unaffected hand (in green). (b) Error rates (mean ± S.E.M.) for laterality judgments of the affected hand (in red) and the unaffected hand (in green). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

3. Results

3.1. Behavioral effects

Reaction times and error rates of the participants are shown in Fig. 1. Reaction times increased with increasing stimulus rotation (main effect of rotation: $F_{(4,28)} = 10.39$; $p = 0.005$; Fig. 1a). Trend analysis indicated that the RTs follow a combination of a linear (contrast estimate = 0.653 ± 0.072, mean ± S.E.; $p < 0.001$) and a quadratic (contrast estimate = 0.209 ± 0.065, mean ± S.E.; $p = 0.001$) increase with rotation, while no higher order trends were visible (3rd order: contrast estimate = −0.061 ± 0.053, mean ± S.E.; $p = 0.25$; 4th order: contrast estimate = −0.016 ± 0.046, mean ± S.E.; $p = 0.73$).

Although reaction times appeared slightly longer for the affected hand than for the unaffected hand, this effect was not statistically significant (main effect of hand: $F_{(1,7)} = 0.94$; $p = 0.37$). Reaction times did not behave differently for the affected and the unaffected hand at different levels of rotation (hand × rotation interaction: $F_{(4,28)} = 0.037$; $p = 0.92$). There were also no differences in reaction time between laterality judgments of the left and the right hand (main effect of hand: $F_{(1,7)} = 0.20$; $p = 0.67$; hand × rotation interaction: $F_{(4,28)} = 0.61$; $p = 0.66$). All patients performed with low error rates (Fig. 1b). There was no difference in error rate between hand laterality judgments of the affected hand and of the unaffected hand ($t_{(7)} = 0.36$, $p = 0.73$).

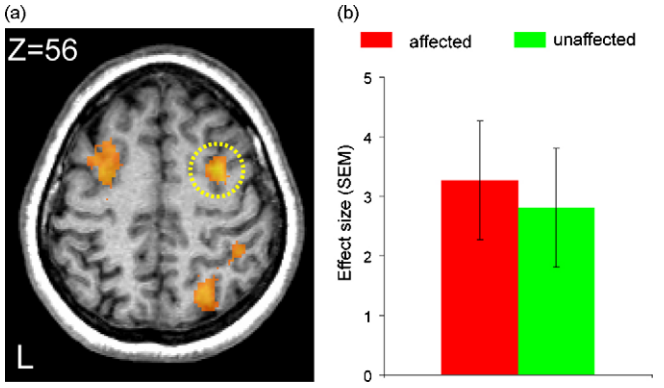

Fig. 2. Regions showing an increase in activity with increasing biomechanical complexity for both hands. (a) Anatomical localization of regions showing a significant linear increase in activity with increasing biomechanical complexity for both hands. The statistical map is thresholded at the same threshold used for inference ($T > 2.8$). (b) Effect size (±S.E.M.) of the parametric effect in the right dorsal precentral sulcus, which is highlighted in panel (a). Exact stereotactic coordinates are given in Table 2.

3.2. Cerebral effects—increases in activity with increasing biomechanical complexity

In line with previous reports (de Lange et al., 2005; Parsons et al., 1995), there was increasing activity with increasing biomechanical complexity in the right dorsal intraparietal sulcus, and in the left and right dorsal precentral sulcus (Fig. 2). These regions showed comparable responses for the affected and the unaffected hand.

There were no clusters that showed differential increases in activity with increasing biomechanical complexity between the affected and the unaffected hand.

3.3. Cerebral effects—activity differences between the affected and unaffected hand

There were several regions showing greater cerebral activity during motor imagery of the affected hand compared to motor imagery of the unaffected hand, independently of the stimulus rotation. There was significantly greater activity for the affected hand in the left superior temporal cortex (Fig. 3a) extending to the parietal operculum, in the prefrontal cortex (Fig. 3c) spanning ventromedial and dorsomedial parts, and in the right superior temporal cortex, at the posterior end of the Sylvian fissure (Fig. 3e). The activity patterns show that these effects relate to reduced responses during motor imagery of the unaffected hand (Fig. 3b, d and f). The observed activity differences were present in all patients in the prefrontal cortex (Fig. 3c), and in 7/8 patients in the left and right temporal (Fig. 3a and e) cortex. Post hoc analyses ruled out that there were any activation differences in these regions as a function of the laterality of the conversion paralysis (prefrontal cortex: $t_{(6)} = -0.34$; $p = 0.75$; left temporal cortex: $t_{(6)} = 0.71$; $p = 0.51$; right temporal cortex: $t_{(6)} = 1.71$; $p = 0.14$).

There were no clusters showing greater overall activity during motor imagery of the unaffected hand compared to the affected hand.

Table 2
Cerebral data—areas showing increasing activity with rotation

Contrast	Region	Pseudo-*T* value	Cluster size	Corrected *p*-value	Stereotactic coordinates		
					x	*y*	*z*
Affected and unaffected	Intraparietal sulcus	5.5	2889	0.012	38	−36	38
		4.8	1226	0.027	−28	−4	46
	Dorsal precentral sulcus	4.0			−26	4	62
		4.3	2889	0.012	28	0	60

All reported coordinates are in MNI (Montreal Neurological Institute) space. Stereotactic coordinates denote the peak of the clusters surviving correction for multiple comparisons.

3.4. Cerebral effects—activity differences between the left and right hand

As illustrated in Fig. 4, there were several regions that modulated their activity as a function of whether a left or right hand was presented on screen. Notably, when patients saw a left hand stimulus they responded with their left foot, and when patients saw a right hands stimulus they responded with their right foot. Accordingly, we observed activity in the contralateral primary motor cortex (medial wall, around the leg area) during task execution of left/right hands. Furthermore, motor imagery of the left hand showed higher activation in the dorsal premotor cortex on the contralateral side, reflecting the additional processing required for motor imagery of the left hand in the dorsal premotor cortex of the contralateral hemisphere (de Lange, Helmich, & Toni, 2006; Parsons et al., 1995, 1998). Notably, these areas were not differentially activated for motor imagery of the affected and of the unaffected hand.

4. Discussion

In this study, we measured cerebral activity in eight CP patients with a unilateral paresis of the arm while they were engaged in a well-known motor imagery task: mental rotation of hands. Motor imagery of the affected hand and the unaffected hand recruited comparable cerebral resources in the motor system, and generated equal behavioral performance. However, motor imagery of the affected hand drew on additional cerebral resources, localized to the medial prefrontal cortex and the superior temporal cortex. Below we detail and interpret these behavioral and cerebral effects.

4.1. Behavioral effects

There were no significant behavioral differences between motor imagery of the affected and the unaffected hand (Fig. 1). These results are in line with an earlier study that observed a behavioral difference only if CP patients were explicitly instructed to imagine performing a rotational movement with their own hand, but only a non-significant trend when they were engaged in implicit motor imagery (Roelofs et al., 2001). Given that the patients could engage in motor imagery of the affected and unaffected hand with comparable behavioral performance, the differences in cerebral activity cannot be a by-product of different task performance. Rather, they reflect qualitative differences in brain activity between imagery of the affected compared to the unaffected hand (Wilkinson & Halligan, 2004).

4.2. Cerebral effects

Motor imagery of both the affected and the unaffected hand evoked activity in the dorsal parietal and premotor cortex. This activity increased with increasing stimulus rotation (Fig. 2). This same parieto-frontal network has also been isolated in earlier studies using similar motor imagery paradigms (de Lange et al., 2005; Johnson et al., 2002), as well as during the selec-

Table 3
Cerebral data—activation differences

Contrast	Region	Pseudo-*T* value	Cluster size	Corrected *p*-value	Stereotactic coordinates		
					x	*y*	*z*
Affected > unaffected	Medial frontal cortex	5.5	1303	0.035	8	44	−24
		5.2			−12	62	32
		6.2			−36	48	34
	Parietal operculum (PO4)	5.8	1065	0.039	−58	−6	10
	Superior temporal sulcus	5.1			−52	−36	−4
	Superior temporal gyrus	5.9	483	0.047	68	−28	10
Left hand > right hand	Primary motor cortex	5.4	4673	0.0039	16	−40	70
	Precentral gyrus	7.0			32	−10	68
Right hand > left hand	Primary motor cortex	7.1	1525	0.0098	−6	−36	64

All reported coordinates are in MNI (Montreal Neurological Institute) space. Stereotactic coordinates denote the peak of the clusters surviving correction for multiple comparisons.

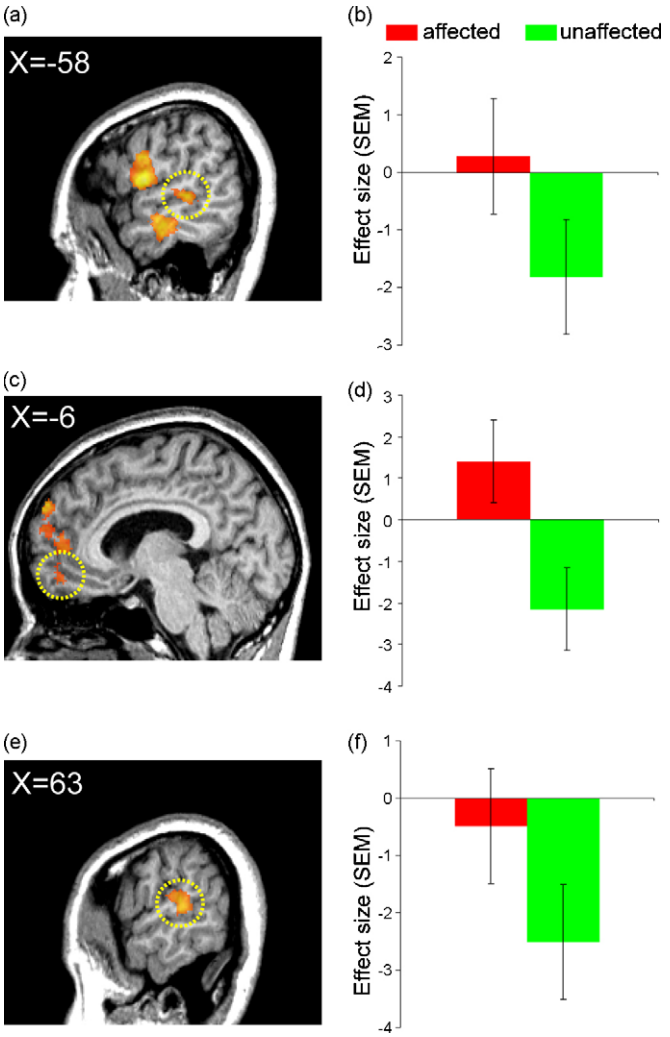

Fig. 3. Regions showing higher activity for the affected than the unaffected hand. Anatomical localization and effect sizes (±S.E.M.) of clusters showing overall (i.e., not rotation-related) higher activity for the affected hand than for the unaffected hand. There was higher activity for the affected limb in the left superior temporal cortex (a and b), medial prefrontal cortex (c and d), and the right superior temporal cortex (e and f). Exact stereotactic coordinates are given in Table 3. Other conventions as in Fig. 2.

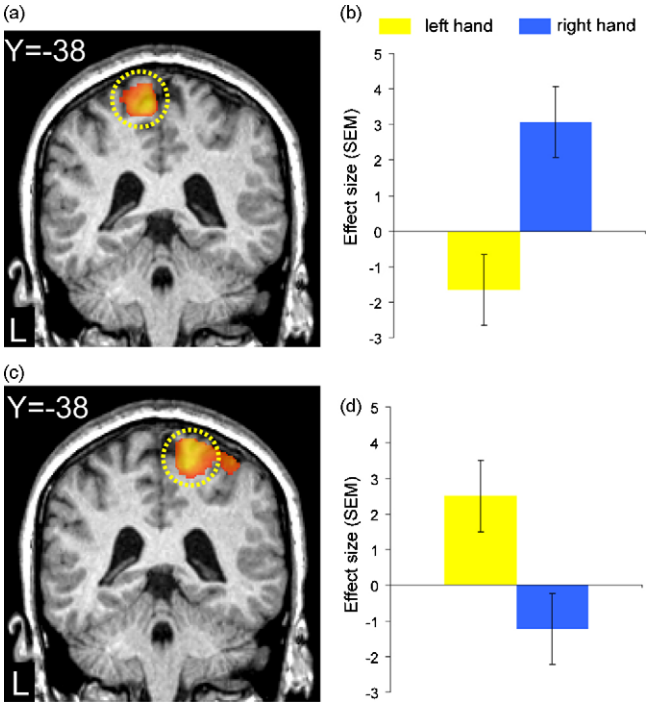

Fig. 4. Regions showing differences in activity between the left and right hand. Anatomical localization and effect sizes (±S.E.M.) of clusters showing overall (i.e., not rotation-related) higher activity for the right hand compared to the left hand (a and b) and for the left hand compared to the right hand (c and d). There was higher activity in the contralateral somatosensory cortex for laterality judgments of left/right hands, which is related to the button press with the left/right foot to respond to each trial. Exact stereotactic coordinates are given in Table 3. Other conventions as in Fig. 2.

tion and preparation of actual hand movements (Rushworth, Johansen-Berg, Gobel, & Devlin, 2003; Thoenissen, Zilles, & Toni, 2002; Toni, Schluter, Josephs, Friston, & Passingham, 1999). Given that both behavioral performance and cerebral activity were not altered, it appears that CP patients can readily imagine actions of both their unaffected and affected hand, using the same cerebral resources as healthy participants. The similar increase of imagery-related cerebral activity for the affected arm in preparatory motor-related structure seems to run counter to the predictions of CP models postulating a reduction of preparatory activity within the motor system, due to increased cognitive inhibitory control (Marshall et al., 1997).

Other cortical regions, outside the motor system, showed stronger responses during motor imagery of the affected than the unaffected hand. Differently from the effect observed in the motor system, these effects were independent of biomechanical complexity. First, we found differential activity between imagined movements of the affected and unaffected hand in the prefrontal cortex (Fig. 3c), comprising both ventromedial and dorsomedial aspects of prefrontal cortex. This result replicates the findings from previous case studies describing increased activity in the ventromedial prefrontal cortex of a CP patient trying to move her paralyzed limb (Marshall et al., 1997), and a hypnotized healthy subject trying to move her "hypnotically paralyzed" limb (Halligan et al., 2000). While our results confirm the involvement of vmPFC during volitional action generation in CP patients, here we show that this involvement arises from a failure to de-activate this region during motor imagery of the affected hand. The vmPFC is part of the "intrinsic" or "default" network (Raichle & Mintun, 2006), showing physiological decreases of metabolic activity during performance of sensori-motor and cognitive tasks (Gusnard, Raichle, & Raichle, 2001). Our results show that, in CP patients, generating motor plans involving the affected hand abolishes these physiological responses: cerebral activity remains at resting-state levels, well above BOLD signals measured during motor imagery of the unaffected hand. This observation is not immediately compatible with accounts of CP that associate vmPFC activity with an increased active inhibitory control of the motor system during the generation of movements involving the affected hand (Halligan et al., 2000; Marshall et al., 1997). The vmPFC effect appears in line with the notion that, in CP patients, simulating movements of the affected hand

is associated with increased self-monitoring processes (Roelofs et al., 2006; Vuilleumier, 2005). Namely, when normal subjects are engaged in a demanding task, there is an inhibition of the prefrontal cortex compared to when subjects are engaged in self-reflexive processing (Goldberg, Harel, & Malach, 2006). In a similar vein, damage to the prefrontal cortex can abolish the awareness of actions (Frith, Blakemore, & Wolpert, 2000). Accordingly, our findings may indicate that, in CP patients, self-referential processes persist during the performance of motor simulations involving the affected hand. It remains to be seen whether these processes are specifically related to monitoring the expected autonomic or emotional consequences of the movement.

There was a second cortical cluster showing higher activity during imagined movements of the affected hand. This cluster covered a rather large portion of the superior temporal cortex (extending into the parietal operculum—Fig. 3a and e), and it showed similar responses to those observed in the medial PFC. This temporal region has been consistently associated with perceptual and cognitive processes like the analysis of biological and implied motion (Allison, Puce, & McCarthy, 2000). Therefore, the hyperactivity of this region during imagined actions of the affected arm may – like the vmPFC – be a reflection of heightened monitoring of actions with the affected limb, but in the visual domain.

4.3. Limitations

A limitation of the present study is our sample size ($N = 8$). However, this is the first study on CP patients in which the statistical model (random effects analysis) allows one to generalize the inferences beyond the sample studied (Friston, Holmes, & Worsley, 1999). Previous studies dealt either with case reports (Marshall et al., 1997) or made sample-specific inferences (Burgmer et al., 2006; Spence et al., 2000; Vuilleumier et al., 2001). Nevertheless, studies using larger sample sizes are clearly needed to investigate whether the (considerable) inter-individual differences in severity of the paralysis are also reflected by, e.g., larger fluctuations in prefrontal and temporal activity during imagined actions. A further limitation of this study is that our data are the result of within-patients comparisons, comparing the affected arm to the unaffected arm. Therefore, possible pathological changes between patients with conversion paralysis and healthy subjects that are independent of the arm cannot be isolated with this study.

5. Conclusions

Our results show that, during imagery of movements with the paralyzed arm, CP patients show similar responses in preparatory motor structures but fail to de-activate the ventromedial prefrontal and superior temporal cortex. These results suggest that the paralysis that characterizes these patients does not manifest itself at the neural level as heightened inhibition of motor processes. Rather, we observed cerebral responses that could be more readily linked to altered monitoring of movements. These findings might provide a neurocognitive background for an effective therapeutic approach like cognitive behavioral therapy, that aim at abolishing perpetuating factors like heightened self-focus in CP (Stone, Carson, & Sharpe, 2005b).

Competing interests

The authors have no competing interests.

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