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The Brain under Self-Control: Modulation of Inhibitory and Monitoring Cortical Networks during Hypnotic Paralysis

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SUMMARY

Brain mechanisms of hypnosis are poorly known. Cognitive accounts proposed that executive attentional systems may cause selective inhibition or disconnection of some mental operations. To assess motor and inhibitory brain circuits during hypnotic paralysis, we designed a go-nogo task while volunteers underwent functional magnetic resonance imaging (fMRI) in three conditions: normal state, hypnotic left-hand paralysis, and feigned paralysis. Preparatory activation arose in right motor cortex despite left hypnotic paralysis, indicating preserved motor intentions, but with concomitant increases in precuneus regions that normally mediate imagery and self-awareness. Precuneus also showed enhanced functional connectivity with right motor cortex. Right frontal areas subserving inhibition were activated by nogo trials in normal state and by feigned paralysis, but irrespective of motor blockade or execution during hypnosis. These results suggest that hypnosis may enhance self-monitoring processes to allow internal representations generated by the suggestion to guide behavior but does not act through direct motor inhibition.

INTRODUCTION

Volition to action is a fundamental feature of our subjective experience of intentionality. Yet, understanding the cerebral mechanisms of volition remains rudimentary. Various brain disorders may disrupt motor actions or motor intentions, implicating a wide network of cortical and subcortical regions responsible for initiating, planning, executing, and monitoring one's actions (Frith et al., 2000). Some psychiatric conditions, such as conversion disorder (Halligan et al., 2000b; Vuilleumier et al., 2001) and schizophrenia (Blakemore et al., 2003; Frith, 2005), may result from uncoupling the execution of movements from the subjective experience of voluntary control over actions. However, changes in the functional relations between volition and action can also be induced in healthy people, typically by using hypnotic suggestion (Blakemore et al., 2003).

Hypnosis is thought to involve a distortion of consciousness, with heightened suggestibility and diminished peripheral awareness (Spiegel and Spiegel, 1978), which can induce various changes in perception, emotion, thought, or behavior. Popular views consider hypnosis as a "sleep-like state" in which an individual acts like an automaton, under the command of a will other than his/her own. In contrast, contemporary scientific accounts have proposed that hypnotic effects might reflect an engagement of specific cognitive processes mediating executive and attentional control (Crawford, 1994; Gruzelier, 1998). Thus, an influential model (Oakley, 1999) suggests that hypnosis might correspond to "the withholding of representations from entry into self-awareness…as the result of the inhibition by the central executive system" of motor or cognitive processes that to the individual are experienced as willed actions or, alternatively, due to some disconnection between executive control and awareness systems (Hilgard, 1974). This model was supported by studies (Blakemore et al., 2003; Haggard et al., 2004) showing that the subjective experience of willing an action can be excluded from awareness by hypnotic induction (e.g., leading to a dissociation between subjective reports of intention to move and actual movement). However, the neural substrates underlying such changes in executive control have not yet been identified.

More recently, functional neuroimaging was used to investigate the neural mechanisms implicated in some effects of hypnosis (Egner et al., 2005; Faymonville et al., 2000; Kosslyn et al., 2000; Rainville et al., 1997; Raz et al., 2005; Szechtman et al., 1998), but most studies focused on pain perception. This pioneer work showed that hypnosis may either reduce or enhance the intensity of experienced pain for physically identical stimuli, in parallel with a modulation of regions in the anterior cingulate cortex (ACC) that encode the affective value of pain (Rainville et al., 1997). However, a modulation of ACC by hypnosis might also reflect the key role of this region in attention and executive control (Carter et al., 1999; Turken and Swick, 1999). In

support of this idea, recent studies have examined the effect of hypnosis on selective attention using Stroop tasks and reported either decreases or increases in ACC depending on the suggestion (Egner et al., 2005; Raz et al., 2005).

Few imaging studies investigated hypnotic effects on other functions. Although these studies elegantly demonstrated an impact of suggestion on neural activity underlying voluntary movement (Halligan et al., 2000a; Ward et al., 2003), color perception (Kosslyn et al., 2000), or memory (Mendelsohn et al., 2008), none directly tested for a "causal" role of inhibition or disconnection of executive control systems in producing these neural changes. Pioneer work on hypnotic leg paralysis (Halligan et al., 2000a; Ward et al., 2003) found that a lack of activation in motor cortex during attempted movements with the affected leg was associated with concomitant increases in ACC and orbitofrontal cortex (OFC) and concluded that the latter activations might be responsible for inhibiting motor cortex. However, it is unclear whether such inhibition involves nonconscious processes specific to hypnosis or bear some similarity with other mechanisms responsible for voluntary inhibitory control in normal (nonhypnotic) conditions. Furthermore, rather than having a causal role in inhibition, the ACC and OFC increased activities during hypnosis might at least partly reflect the important function of these regions in processing conflicts and motivational choices, in keeping with the discrepancy between hypnotic suggestion of paralysis and instructions to move (de Lange et al., 2007).

Here, we used fMRI to directly test whether a hypnotic suggestion of paralysis may activate specific inhibitory processes and whether these may or may not correspond to those responsible for inhibition in nonhypnotic conditions. We designed a go-nogo paradigm that allowed us to compare these different types of inhibition within a single task. Go-nogo paradigms have been extensively used to study motor inhibition and are known to recruit selective brain regions, particularly the right inferior frontal gyrus (IFG; see Aron et al., 2004b; Garavan et al., 1999). Moreover, the right IFG mediates inhibition for a wide range of behaviors, including not only prepotent responses but also inappropriate thoughts (Anderson et al., 2004) or memories (Depue et al., 2006). In our study, by comparing performance in a go-nogo task under normal conditions and under hypnotic suggestion of paralysis for one hand, we could determine whether voluntary inhibition of an action (e.g., no-go condition for a "normal" hand) and hypnotic paralysis (e.g., go condition for a "paralyzed" hand) would share similar neural mechanisms (i.e., activation of right IFG or ACC). In addition, our go-nogo task was combined with a motor preparation phase, during which subjects had to prepare a hand movement prior to the imperative GO or NOGO cue. If hypnotic paralysis involves a suppression of motor intention, then the preparation phase should evoke no motor activation for the paralyzed hand (and no subsequent inhibition). Alternatively, if hypnotic paralysis involves an active inhibition of willed movement (Halligan et al., 2000b), then activation of motor and premotor areas should arise normally during preparation, while inhibitory activity should arise at the time of execution (e.g., left go trials should actually correspond to the no-go conditions). Furthermore, based on the idea that hypnosis may induce a functional dissociation between discrete brain networks (Egner et al., 2005; Jamieson and Sheehan, 2004), we tested for any change in the functional connectivity of motor regions during hypnosis and normal state. Importantly, to determine effects specific to hypnosis, we compared a group of subjects during hypnotic paralysis with a group of subjects instructed to simulate paralysis without hypnotic suggestion.

Our results reveal that hypnotic paralysis differs from active voluntary motor inhibition but selectively modulates activity in brain areas involved in self-monitoring and attentional control, decreasing functional connectivity of the primary motor cortex with premotor areas while increasing connectivity with regions in precuneus that are associated with mental imagery and self representations.

RESULTS

All participants performed a go-nogo task using both hands (see Experimental Procedures). Each trial began with a preparation cue (black-and-white picture of a right or left hand), indicating the side to prepare the upcoming movement (PREP condition). Then, the hand picture could turn either green or red: when green, participants had to press a button as quickly as possible with the corresponding hand (GO condition, 75% of trials); but when red, the prepared movement had to be withheld (NOGO condition, 25% of trials).

A group of participants (n = 12) performed this task in a normal state for two consecutive blocks and in a hypnotic state for two other consecutive blocks (order counterbalanced). During hypnosis, subjects received a suggestion that their left hand was paralyzed, prior to performing the task and starting fMRI scans (see Experimental Procedures).

A control group (n = 6) performed the same task but with the instruction to simulate a left-hand paralysis. They were told to act "as if" they were suffering from motor weakness and unable to move their fingers. This simulation group provided an important control for the possibility that hypnosis could be feigned and paralysis voluntarily produced in the previous group.

Behavioral Performance

In the normal state, participants correctly responded with both hands for GO (97.4%) as well as NOGO conditions (96.9%). During hypnosis and simulation, performance was also highly accurate with the right hand for GO (97.9% and 95.8%, respectively) and NOGO trials (97.5% and 96.4%, respectively), whereas no movement was made with the left hand (Table 1), indicating successful hypnotic suggestion and compliance with our instruction in the two groups. Likewise, RTs on correct GO trials with the right hand were similar in all conditions (normal state, hypnosis, or simulation; Table 1). ANOVAs and paired t tests on accuracy and RT data showed no significant difference between hands in the normal state and between states for the right hand (all pairwise comparisons, $t < 1$, for both RTs and error rates). These behavioral data demonstrate that hypnosis did not impair the task performance for the nonaffected hand.

fMRI Data

Our design allowed us to test for two main hypotheses on the neural mechanisms of hypnotic motor paralysis. First, by examining brain activity during the preparation phase, we could

Table 1. Behavioral Performance

	L Hand			R Hand		
	Normal	Hypnosis	Simulation	Normal	Hypnosis	Simulation
RT (ms)	442	0	0	435	439	439
	(±SD 11)			(±SD 11)	(±SD 10)	(±SD 17.6)
Errors (%)	2.9	0.1	0	2.2	2.2	3.75
	(±SD 0.6)	(±SD 0.1)		(±SD 0.3)	(±SD 0.5)	(±SD 1.8)

determine whether hypnotic induction acted by suppressing motor intentions or by inhibiting movements still normally intended for the left hand. Second, by comparing induced paralysis on go and no-go trials, we could determine whether any active inhibition of the left hand during hypnosis (on go trials) might implicate similar neural processes as the voluntary suppression of a prepared movement (on no-go trials). Alternatively, hypnosis might act on motor function through a distinct modulation or disconnection of executive control systems (Egner and Raz, 2007), in particular the putative inhibitory processes mediated by IFG and ACC (Aron et al., 2004b; Halligan et al., 2000b).

Movement Preparation under Hypnosis

To test whether hypnotic paralysis affected motor preparation, we examined brain activity during the presentation of the PREP cues, for one or the other hand (R-PREP > L-PREP, and conversely). In the normal state, there was a reliable activation of motor cortex (M1), contralateral to the hand being prepared (Figure 1 and Table 2A). The same pattern was found during hypnosis and simulation (Table 2). For the hypnosis group, a 2 (hand-side) × 2 (state) ANOVA on parameter estimates of activity (betas) from the right M1 showed a main effect of hand-side [$F_{(1,11)} = 39.49$, $p < 0.001$] but no significant effect of state and no interaction [$F_{(1,11)} < 1.34$, n.s.]. For simulation relative to normal state, a similar 2 (hand-side) × 2 (group) ANOVA also showed a main effect of hand [$F_{(1,11)} = 24.54$, $p < 0.001$], with no interaction [$F_{(1,11)} = 0.25$, n.s.]. Thus, despite left hypnotic paralysis or simulation, participants still normally activated their right M1 during preparation of a left-hand movement, indicating that they could still generate covert motor plans and correctly followed task instructions (Toni et al., 1999). However, preparation of the left hand also activated a second cluster in somatosensory cortex under both hypnosis and simulation (Table 2), not in the normal state (z score = 1.18, n.s. for the same coordinates).

In addition, the same contrast (L-PREP > R-PREP) showed a selective increase in the precuneus for movement preparation with the left/paralyzed hand during hypnosis (Figure 1 and Table 2A). By contrast, in the normal state and simulation condition, as well as for the right hand under hypnosis, activity in this region was generally low and similar for both hands (L-PREP versus R-PREP in normal state: z score = 0.31; simulation: z score = 1.06; both n.s.). This differential activity across hands and conditions suggests a specific involvement of the precuneus in the hypnotic suggestion concerning the left hand (see Figure 1).

Finally, direct contrasts between hypnosis and normal conditions (for right or left hand preparation separately) revealed higher activity in visual areas and right middle temporal gyrus irrespective of the hand used (Table 2B). These direct contrasts also confirmed the absence of significant differences in motor cortex for either side (right, xyz = 39, –30, 54, z score = 0.89; left, xyz = –42, –18, 45, z score = –0.27, both n.s.) but selective increases in the precuneus for the left hand only during hypnosis (Table 2B) and not for the right hand (left precuneus peak: xyz = –3, –63, 57, z score = 0.31; right peak: xyz = 9, –63, 45, z score = 1.12, both n.s.).

Motor Execution

Next, we identified activations produced by motor execution (in normal conditions) or attempted movements (under hypnosis)

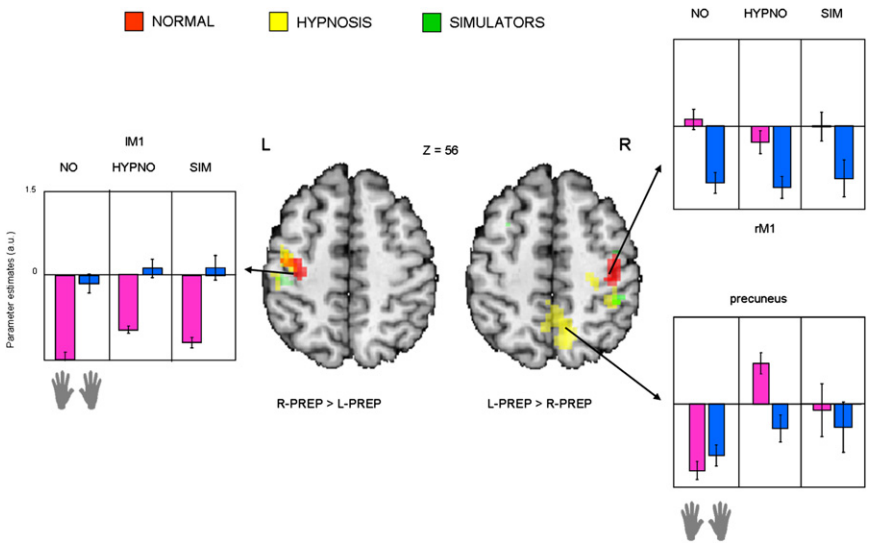

Figure 1. Activation during Preparation Phase

Regions showing an increase in the PREP condition for the right > left/paralyzed hand (left section of the figure) and for the left/paralyzed > right hand (right section of the figure) in normal state (red), hypnosis (yellow, $p < 0.001$ uncorrected, $k = 20$ voxels), and simulation (green, $p < 0.005$ uncorrected, $k = 40$ voxels). Plots represent parameter estimates (beta values, error bars represent ±1 SEM for each column) for L-PREP (pink) and R-PREP (blue) in normal (NO), hypnosis (HYPNO), and simulation (SIM) conditions. Bilateral and symmetric activations can be seen in primary motor cortex in all cases. Increases in precuneus were observed under hypnosis for the left hand selectively (see text). Additional activity in somatosensory cortex was also seen during hypnosis and simulation.

Table 2. SPM Results for the Motor Preparation Phase

A.	Hemisphere	Brain Region	x	y	z	Z Value
NO: L-PREP > R-PREP						
	R	motor cortex	39	−30	54	4.57
NO: R-PREP > L-PREP						
	L	motor cortex	−42	−18	45	4.34
	L	SMA	−6	−15	45	3.79
	L	thalamus	−6	−15	12	3.56
HYPNO: L-PREP > R-PREP						
	R	motor cortex	27	−30	60	4.83
	R	precuneus	9	−63	57	4.36
	R	precentral gyrus	39	−15	51	4.33
	R	S1	42	−39	51	4.21
	R	inferior parietal lobule	54	−33	30	3.61
HYPNO: R-PREP > L-PREP						
	L	motor cortex	−39	−18	51	4.55
SIM: L-PREP > R-PREP						
	R	motor cortex	45	−12	60	3.08*
	R	inferior parietal lobule	45	−45	54	4.21
SIM: R-PREP > L-PREP						
	L	motor cortex	−45	−30	54	3.03
	R	middle frontal gyrus	39	33	−3	4.34
	L	middle temporal gyrus	−54	−63	12	3.78
	L	posterior insula	−39	−21	15	3.73
	L	superior temporal gyrus	−57	−39	15	3.62
	R	ventral premotor cortex	57	−6	18	3.34
B.	Hemisphere	Brain region	x	y	z	Z Value
L-PREP: HYPNO > NO						
	R	precuneus	9	−63	45	5.03
	L	precuneus	−3	−63	57	4.2
	R	lingual gyrus	3	−90	−12	4.46
	R	middle temporal gyrus	45	−54	0	4.78
	L	thalamus	−15	−6	15	4.7
	R	precentral gyrus	51	−9	39	4.18
R-PREP: HYPNO > NO						
	R	lingual gyrus	6	−81	−3	4.36
	R	middle temporal gyrus	48	−60	0	3.97
	R	thalamus	18	−21	−3	4.77

NO, normal state; HYPNO, left hypnotic paralysis; SIM, left simulated paralysis, *k = 5 voxels instead of 20.

by comparing GO relative to NOGO trials, for each hand separately (Table 3A). These analyses showed that left motor networks (including left M1 and right cerebellum), were significantly recruited by right-hand movements (R-GO > R-NOGO) with a similar response in all conditions (normal, hypnosis, or simulation; Figure 2 and Table 3A). For the hypnosis group, a 2 (task-condition) × 2 (state) ANOVA on betas from the left M1 confirmed a main effect of task-condition [$F_{(1,11)} = 220{,}37$, $p < 0.001$] with no significant effect of state and no interaction [$F_{(1,11)} < 4.17$], whereas for simulation relative to normal state, a 2 (task-condition) × 2 (group) ANOVA showed a main effect of task-condition [$F_{(1,11)} = 125.06$, $p < 0.001$] but no interaction [$F_{(1,11)} < 4.10$].

By contrast, left motor execution (L-GO > L-NOGO) activated motor areas (including right M1 and left cerebellum) in the normal condition only (Figure 2 and Table 3A). The same comparison during hypnotic paralysis showed no such motor increases (Table 3A; z score = 1.03, n.s. for right M1 peak), consistent with the lack of executed movement on L-GO (Table 1). Accordingly, in the hypnosis group, the 2 (condition) × 2 (state) ANOVA for right M1 activity revealed a significant interaction [$F_{(1,11)} = 53.22$, $p < 0.001$], together with main effects of condition [$F_{(1,11)} = 97.48$, $p < 0.001$] and state [$F_{(1,11)} = 10.26$, $p = 0.008$]. Likewise, for simulation relative to normal state, a 2 (condition) × 2 (group) ANOVA also showed a significant interaction

Table 3. SPM Results for the Motor Execution Phase

A.	Hemisphere	Brain Region	x	y	z	Z Value
NO: R-GO > R-NOGO						
	L	motor cortex	−33	−18	63	4.57
	L	insula	−57	−12	9	3.69
HYPNO: R-GO > R-NOGO						
	L	motor cortex	−54	−24	51	5.6
	R	motor cortex	57	−15	48	5.05
	R	inferior parietal lobule	63	−30	21	4.89
	L	SMA	−3	−15	51	4.88
	L	anterior cingulate cortex	−6	33	21	4.03
SIM: R-GO > R-NOGO						
	L	motor cortex	−48	−12	51	3.93
	R	inferior precentral gyrus	48	0	27	4.15
NO: L-GO > L-NOGO						
	R	motor cortex	51	−24	60	5.41
	L	insula	−42	−3	9	4.44
	L	motor cortex	−51	−30	60	4.36
	L	cuneus	−3	−69	30	4.31
	R	insula	36	6	9	3.85
	R	post-ACC	3	3	33	3.84
HYPNO: L-GO > L-NOGO						
	L	middle occipital gyrus	−24	−99	−3	4.08
	L	lingual gyrus	−24	−90	−12	3.81
SIM: L-GO > L-NOGO						
	R	ACC	15	30	39	4.11
B.	Hemisphere	Brain Region	x	y	z	Z Value
R-GO: HYPNO > NO						
		n.s.				
L-GO: HYPNO > NO						
	L	inferior frontal gyrus	−42	12	−18	3.95
	L	superior frontal gyrus	−3	36	57	3.71

NO = normal state; HYPNO = left hypnotic paralysis; SIM = left simulated paralysis.

[$F_{(1,11)} = 54.46$, $p < 0.001$] and a main effect of condition [$F_{(1,11)} = 36.50$, $p < 0.001$] but no effect of group [$F_{(1,11)} < 4.01$].

Activation of Inhibitory Networks during Hypnotic and Feigned Paralysis

Importantly, no other activation was specifically evoked under hypnosis for L-GO relative to NOGO trials, except for some increases in visual areas (Table 3A). However, if hypnotic paralysis results from active inhibition of motor outputs (Marshall et al., 1997), a key prediction would be that GO trials should elicit a distinct pattern of activation for the left/paralyzed hand so as to stop motor commands that were still normally prepared in motor cortex (see above). Accordingly, activity on left GO trials could possibly become similar to left NOGO trials. We therefore compared the execution phase for one hand versus the other (L-GO > R-GO and vice versa), to identify any activation specific to attempted movements with the left/paralyzed hand under hypnosis. As expected, right movements were found to produce increases in the contralateral left M1 (xyz = –51, –27, 54, z score = 4.67, $p < 0.001$), whereas left "inhibited" movements produced no response in right M1 (xyz = 51, –24, 60, z score = –0.20, n.s.) but selective increases in the left prefrontal areas (xyz = –42, 12, 36, z score = 3.93, $p < 0.001$). Critically, however, there was no activation of brain regions typically associated with cognitive or motor inhibition, such as the right IFG (Aron and Poldrack, 2006; Garavan et al., 1999; Kawashima et al., 1996; Konishi et al., 1999) or ACC, even at liberal threshold (see also below and Figure S1B available online). These results indicate that motor circuits were "silent" during GO trials for the left/paralyzed hand, with no evidence for active inhibition of motor commands.

Finally, direct whole-brain contrasts between hypnosis and normal state also showed that the L-GO condition evoked higher activity in left prefrontal areas under hypnosis, including the inferior and superior frontal gyri (Table 3B). Again, there was no other activation. No significant difference was found for the R-GO conditions across the whole brain (including for direct comparison in left motor cortex, peak xyz = –42, –18, 45, z score = 1.05, n.s.).

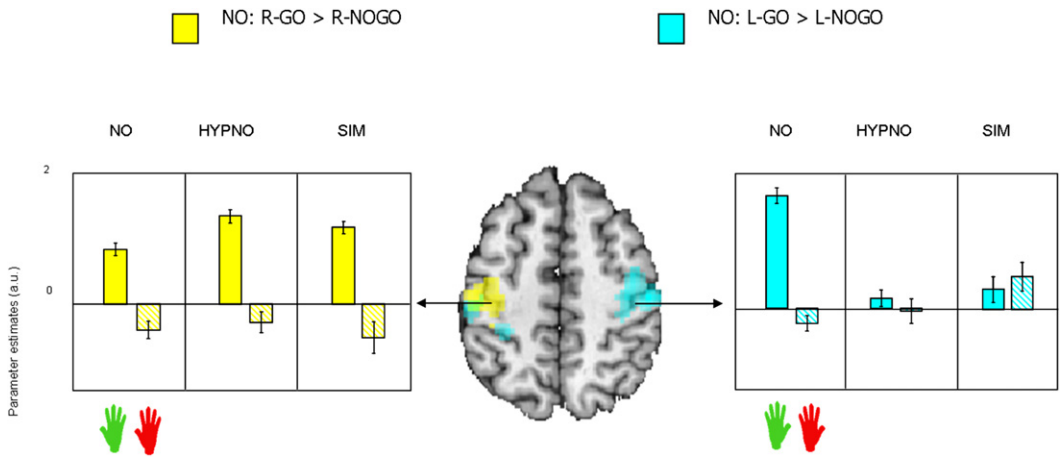

Figure 2. Activations of the Primary Motor Cortex during Motor Execution

Regions showing an increase to GO compared to NOGO trials in the normal state for the left (red) and right (yellow) hands ($p < 0.001$ uncorrected, $k = 20$ voxels). Plots represent the betas for L-GO and R-GO (yellow), plus L-NOGO and R-NOGO (blue) trials, respectively, in the normal, hypnosis, and simulation conditions. Error bars represent ±1 SEM for each column. Consistent with induced paralysis of the left hand, no right motor activation was observed during hypnosis and simulation for L-GO conditions, whereas the left primary motor cortex was activated for R-GO in all three conditions (see text).

By contrast, during feigned paralysis, the left GO condition (compared to R-GO) activated a distinct network of regions including the right IFG (peak xyz = 60, 24, 27, z score = 2.98, p = 0.001), as well as the right IPL (peak xyz = 63, –45, 36, z score = 3.08, p = 0.001), partly overlapping with activations during normal voluntary inhibition, as we could further establish in the next analysis of NOGO trials (see below and Figure S1C).

Voluntary Motor Inhibition

To identify brain regions specifically activated by motor inhibition, we compared NOGO versus GO trials. In the normal state, this contrast revealed a bilateral but right predominant network involving IFG, posterior middle frontal gyrus (post-MFG) gyrus, and IPL (Figure 3 and Table 4 for details), consistent with previous work on motor or cognitive inhibition (Chambers

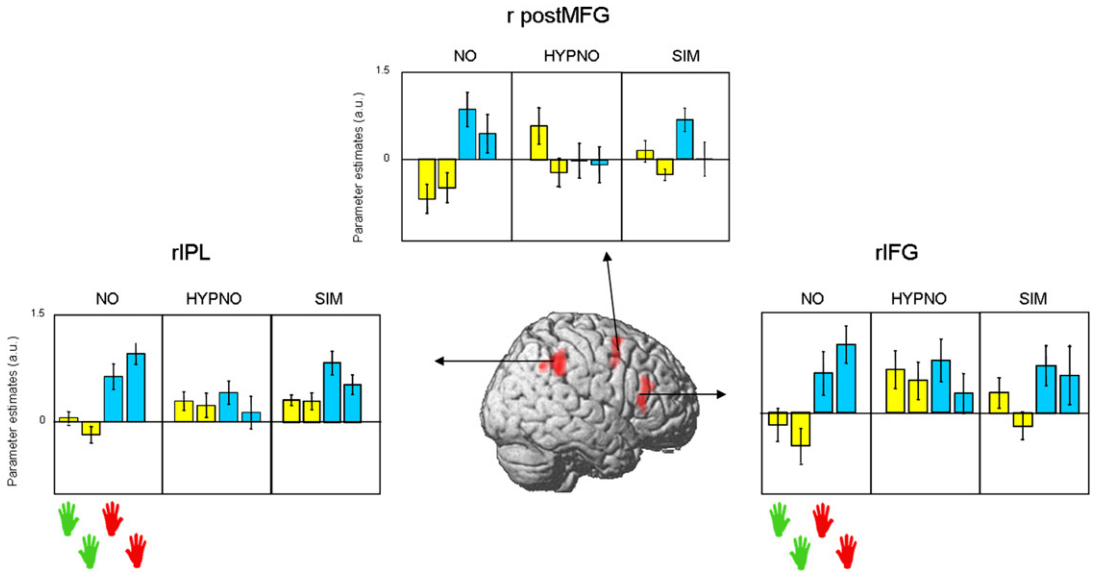

Figure 3. Activation of Inhibitory Networks

A contrast between NOGO > GO trials in the normal state (irrespective of hands) revealed increased activity in a bilateral but predominantly right hemisphere network including inferior frontal gyrus (IFG), posterior middle frontal gyrus (post-MFG), and inferior parietal lobule (IPL); threshold $p < 0.001$ uncorrected, $k = 20$ voxels. Plots represent the betas for L-GO and R-GO (yellow), plus L-NOGO and R-NOGO (blue) trials, respectively, in the normal, hypnosis, and simulation conditions. Error bars represent ±1 SEM for each column. Simulation produced similar increases during normal inhibition (NOGO trials) and feigned left hand paralysis (left GO trials), whereas hypnosis produced a very different pattern with increased activation in IFG and reduced activation in IPL in all NOGO and GO conditions (irrespective of hands; see text for statistical comparisons). Posterior MFG was selectively activated for L-GO during hypnosis, unlike NOGO activation in the normal condition.

Table 4. SPM Results for the Motor Inhibition Phase

	Hemisphere	Brain region	x	y	z	Z Value
NO: NOGO > GO						
	R	middle frontal gyrus	42	6	60	4.93
			39	3	42	4.05
	R	supramarginal gyrus	54	−42	36	4.53
	L	inferior frontal gyrus	−54	30	0	4.43
	L	middle temporal gyrus	−60	−42	−3	4.14
	R	middle temporal gyrus	51	−21	−12	4.01
	R	inferior frontal gyrus	57	30	24	4.08
			57	24	9	3.77
	L	inferior frontal gyrus	−42	18	−6	3.78
HY: NOGO > GO						
		n.s.				
SIM: NOGO > GO						
	R	middle temporal gyrus	48	−42	0	3.56
	L	middle frontal gyrus	−48	24	33	3.93
	R	middle frontal gyrus	45	30	27	3.77
	R	inferior parietal lobule	51	−48	42	3.71

et al., 2007; Chikazoe et al., 2008; Garavan et al., 1999; Menon et al., 2001). There was no significant difference when comparing L-NOGO and R-NOGO trials in the normal state (whole-brain contrast), suggesting that there was no hemispheric lateralization for motor inhibition in the normal state.

Under hypnosis, no such increases were found for the contrast between NOGO versus GO trials (whole brain, Table 4). However, inspecting activity across conditions in the above regions revealed that their response was strongly modified during hypnosis as compared with the normal state (Figure 3), but comparable in both the GO and NOGO conditions, resulting in a lack of significant difference in this contrast. On the one hand, the right IFG was activated across all conditions during hypnosis, for both hands (similar to NOGO in the normal state). A 2 (state) × 2 (hand) × 2 (task-condition) ANOVA on betas from IFG showed significant state × task-condition interaction [$F_{(1,11)} = 22.71$, $p = 0.001$], with significant increases for the GO condition in hypnosis versus normal state across both hands ($t_{11} > 2.32$, $p < 0.05$) but no difference between NOGO and GO in hypnosis ($t_{11} = 0.11$, n.s.). On the other hand, activation in the right IPL was also similar across all conditions during hypnosis, for both hands, but globally reduced as compared with the NOGO conditions in normal state (Figure 3). A similar 2 × 2 × 2 ANOVA on betas from IPL also indicated a significant state × task-condition interaction [$F_{(1,11)} = 78.81$, $p < 0.001$], with significant decreases for NOGO trials under hypnosis relative to normal state ($t_{11} = 3.12$, $p = 0.010$) and no difference between NOGO and GO under hypnosis ($t_{11} = -0.21$, n.s.). Thus, hypnosis produced an apparent dissociation in the pattern of activation of brain areas normally associated to inhibition, with general increases of right IFG and general decreases of right IPL. Finally, the right post-MFG was selectively activated during the critical L-GO trials (see Figure 3; $t_{11} = 2.82$, $p = 0.017$ for L-GO versus R-GO during hypnosis), unlike the normal state where it was activated in NOGO trials with either hand (Table 4 and Figure 3; $t_{11} = -0.74$, n.s., for L-GO versus R-GO in normal state).

By contrast, simulation of left motor paralysis produced a similar activation of the right IFG for normal inhibition (right and left NOGO trials) and for feigned paralysis of left-hand movement (i.e., voluntary inhibition on L-GO trials; see above and Figure 3). This was verified by pairwise contrasts relative to the "normal" R-GO condition during simulation (using a 10 mm sphere centered on the peak of the main effect R + L NOGO > R-GO in this group, xyz = 54, 30, 24): L-GO, z score = 2.98, p = 0.001; L-NOGO, z score = 2.82, p = 0.002; R-NOGO, z score = 2.53, p = 0.006, all contrasted to R-GO; but L-NOGO versus L-GO, z score = 2.18, $p > 0.01$).

Finally, we also compared NOGO trials for the left versus right hand under hypnosis (whole-brain contrast) to determine whether motor inhibition might actually differ between hands in this condition. For the left/paralyzed hand (L-NOGO > R-NOGO), this contrast revealed a selective increase in activity for the left IFG (peak xyz = –54, 27, 15; z score = 3.67, $p < 0.001$). However, as shown in Figure 4, this region was activated not only by left NOGO but also by left GO trials during hypnosis (L-GO > R-GO, peak xyz = –48, 30, 18, z score = 3.16, $p < 0.001$), unlike in the normal state (see above), suggesting a more general modulation related to the left hand motor control rather than to inhibition only (see above). Simulation produced an intermediate pattern between hypnosis and normal state (Figure 4).

Taken together, these data reveal that hypnotic paralysis induced a profound reconfiguration of activity within executive control systems mediated by anterior prefrontal and parietal areas across both hemispheres, which was distinct from voluntary simulation of paralysis and distinct from inhibition of motor responses in the normal state.

Main Effect of Hypnotic State

For completeness, we also tested for any global change in brain activity during hypnosis as compared with the normal state, irrespective of the motor task conditions. This analysis revealed

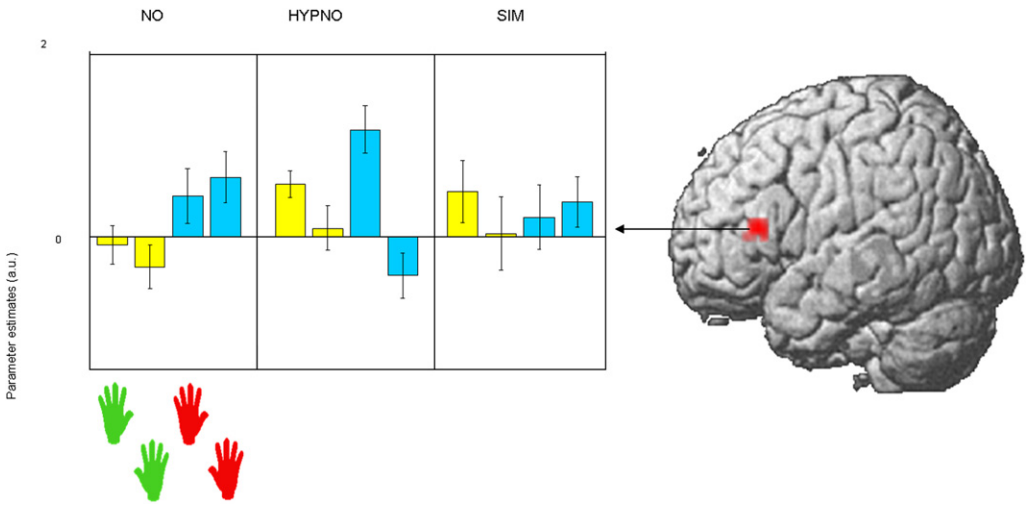

Figure 4. Changes during Motor Response and Inhibition under Hypnosis

A contrast between L-NOGO and R-NOGO trials in the hypnotic state showed selective increases in left prefrontal cortex (threshold $p < 0.001$ uncorrected, $k = 20$ voxels). Plots represent the betas for L-GO and R-GO (yellow), plus L-NOGO and R-NOGO (blue) trials, respectively, in the normal, hypnosis, and simulation conditions in the cluster defined by this contrast (peak xyz = −54, 27, 15). Error bars represent ±1 SEM for each column. Left inferior frontal gyrus showed increased activity for all left-hand trials (GO and NOGO) during hypnosis, but for NOGO trials with both hands during normal state (see text). In the simulation group, the same region showed a mixed pattern.

general increases during hypnosis in right ACC, bilateral orbitofrontal cortex (OFC), and bilateral extrastriate visual areas (see Figure S1). The reverse contrast showed general decreases in activity during hypnosis in the auditory cortex on both sides.

Functional Connectivity

Because some theoretical accounts have proposed that hypnosis might induce a disconnection or "decoupling" between prefrontal and posterior regions (Hilgard, 1974; Woody and Farvolden, 1998), we also investigated the functional connectivity of motor cortices with the rest of the brain as a function of state. Since our hypnotic suggestion of left-hand paralysis indeed produced a lack of left movement and suppressed activation of right M1 (see above), we hypothesized that the latter region should be selectively disconnected from regions involved in voluntary motor control, such as premotor areas, but concomitantly more coupled with other brain regions involved in the hypnotic induction. We first selected the peak of activity in right motor cortex (based on results for L-GO trials in normal state, see above) and then compared the functional connectivity of this region between hypnosis and normal state by whole-brain contrasts (see Experimental Procedures).

Our results showed significant changes in the connectivity of right M1 (Figure 5 and Table 5): in the normal condition, right M1 was more connected to the right dorsal premotor cortex and to the left cerebellum; whereas during hypnosis this region was more connected to the right angular gyrus and left precuneus. Moreover, both the premotor and precuneus regions that were differentially coupled with right M1 activity across states overlapped with brain areas that were differentially activated by left-hand preparation during normal state and hypnosis, respectively (see Table 2 and Figure S2). The connectivity of right M1 in the simulation group was similar to the connectivity observed in the normal condition for the precuneus, the right premotor cortex, and the right angular gyrus ($t_{16} = 0.52$, $t_{16} = 0.23$, and $t_{16} = 0.67$, respectively, all n.s., see also Figure 5).

Conversely, the same analysis for left motor cortex did not show any significant changes in connectivity between normal state and hypnosis.

DISCUSSION

The fascinating alterations of mental functions induced by hypnosis are unlikely to be mediated by any single brain region, but rather involve distributed changes in brain networks supporting conscious will and self awareness. The neural correlates of hypnotic phenomena have remained poorly known, and are still rarely studied, but recent theoretical accounts proposed that hypnosis might entail either active inhibition or disconnection of some mental processes from executive control systems mediated by anterior prefrontal and anterior cingulate areas (Egner et al., 2005). However, these hypotheses have never been directly tested. In line with previous PET studies reporting a key role for ACC and OFC in hypnotic effects on pain (Rainville et al., 1999) and motor behavior (Halligan et al., 2000a), we found increased activity in these regions across all conditions (main effect) but there was no task-specific modulation. This pattern indicates an effect of "state" that was not directly related to inhibitory processes underlying hypnotic paralysis, unlike previously thought (Halligan et al., 2000b; Marshall et al., 1997; Ward et al., 2003), but likely to reflect more general attentional and motivational factors associated with enhanced focusing and monitoring during hypnosis. Further, by systematically comparing different aspects of motor control (preparation, execution, inhibition), we could demonstrate that hypnotic paralysis did not result from active suppression of motor outputs by

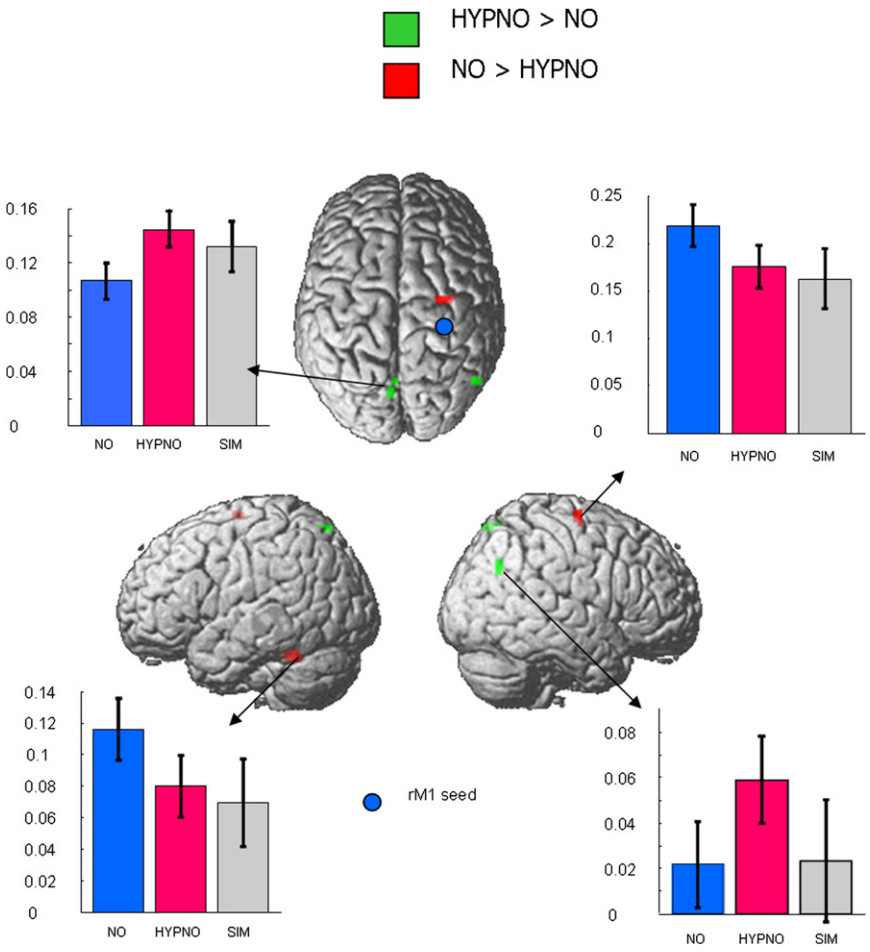

Figure 5. Functional Connectivity of the Right Primary Motor Cortex

Regions showing an increase in correlated activity with the right M1 (blue seed) during the normal state as compared with the hypnotic state (i.e., right precuneus and right inferior parietal lobule, green), and conversely a decrease in correlated activity (i.e., right premotor cortex and left cerebellum, red) at a threshold $p < 0.001$ uncorrected, $k = 5$ voxels. The betas of connectivity with rM1 are plotted for each of these regions for the normal state, hypnosis, and simulation condition. Error bars represent ±1 SEM for each column.

right IFG, unlike voluntary inhibition (on NOGO trials) or simulation of paralysis. These findings argue against a selective recruitment of inhibitory control systems in anterior or medial prefrontal regions during hypnosis.

Instead, our results show that hypnosis produced distributed changes in prefrontal and parietal areas involved in attentional control, together with striking modifications in the functional connectivity of M1 with other brain regions. Changes in connectivity involved a reduced coupling with premotor areas but increased coupling with the precuneus, which was also selectively activated during instructions to prepare left movement during hypnosis. Altogether, these data suggest a disconnection of motor commands from normal voluntary processes, presumably under the influence of brain systems involved in executive control and self-related imagery, as we discuss in details below.

Modulation of Imagery and Self-Referential Processing

Despite the suggestion of paralysis, right M1 was still normally activated during instructions to prepare a left-hand movement under hypnosis (see Figure 1), indicating that hypnosis did not produce a complete suppression of activity in motor pathways and did not totally eliminate the representation of motor intentions (Jeannerod, 2001). Hence, mechanisms of hypnotic paralysis may differ from those postulated for other psychologically induced paralyses such as hysterical conversion (Fiorelli et al., 1991; Vuilleumier, 2005) and from neurological conditions characterized by unilateral losses in movement intentions such as motor neglect (de Lange et al., 2007; Laplane and Degos, 1983). This preserved activation of M1 during preparation is consistent with residual motor imagery despite paralysis (Jeannerod, 2001). In addition, selective increases in the precuneus and extrastriate visual areas were also observed during the preparation of left-hand movements under hypnosis, providing further support for a recruitment of mental imagery processes in this condition.

Several hypotheses can be proposed concerning the role of precuneus activation. First, this region is critically involved in multisensory mental imagery and memory, particularly in relation

Table 5. Functional Connectivity of Right M1

	Hemisphere	Brain Region	x	y	z	Z Value
NO > HYPNO						
	R	middle frontal gyrus	27	−9	66	4.03
	L	cerebellum	−33	−48	−24	3.88
HYPNO > NO						
	L	precuneus	−3	−69	63	3.67
	R	supramarginal	51	−66	33	3.54

to representations of the self (den Ouden et al., 2005; Lou et al., 2004) and self-oriented processes (Boly et al., 2007; Cavanna and Trimble, 2006), including experience of agency (Cavanna, 2007). Furthermore, this area was reported to be specifically activated when envisioning future events from a first-person perspective (Szpunar et al., 2007). This appears consistent with the present activation during motor preparation, since the latter condition constitutes a prospective phase during which the subject could anticipate the upcoming action and intensify a feeling of personal or ''internal'' control over movements rather than a more stimulus-driven or ''external'' control of action. Changes in precuneus activity could also mediate the change in consciousness associated with hypnosis, typically characterized by reduced alertness and/or temporary distortion in representations of the self or the environment (Crawford et al., 1992), in agreement with dysfunctions observed in this region during various states of altered consciousness, such as coma (Laureys et al., 2004), vegetative states (Laureys et al., 1999), sleep (Maquet et al., 2000), or anesthesia (Alkire et al., 1999). In keeping with this idea, a number of previous studies reported modifications in precuneus activity during hypnosis, including a negative correlation with the degree of subjective absorption (Rainville et al., 2002) and some reduction relative to the alert resting state (Maquet et al., 1999). However, it is possible that hypnosis might produce different modulations in precuneus depending on the induction procedure: hypnotic states with no specific suggestion (e.g., relaxation and absorption) tend to reduce precuneus activity, whereas more specific suggestions (e.g., higher or lower pain perception) tend to increase it (Rainville et al., 1999). Here, we found an activation of the precuneus specifically when instructing the subject to prepare a movement with the left/paralyzed hand. Thus, our results do not only confirm that precuneus activity is enhanced during hypnosis with suggestion but also demonstrate that such increases are specifically linked to the target of the suggestion (here the left hand).

Alternatively, changes in precuneus activity might reflect the role of this region in the ''default mode network,'' which is typically more active during rest with closed eyes than during active tasks (Raichle et al., 2001). Hence, our results could be interpreted as a relative lack of suppression of precuneus activity during task performance, with the subject under hypnosis staying in a ''default mode'' when asked to prepare a movement with his left/paralyzed hand. However, because motor preparation was preserved and reaction times with the right hand were unchanged during hypnosis, we consider that a general alteration in consciousness or reduced vigilance did not occur and could not account for selective precuneus activity during left movement preparation. This apparent paradox of preserved volition with concomitant changes in self consciousness might contribute to one of the core phenomena of hypnosis, that is, ''psychic dissociation'' (Hilgard, 1974).

Most importantly, our functional connectivity analysis revealed that a similar region in precuneus showed stronger coupling with right M1 during left hypnotic paralysis, relative to the normal state. Conversely, right M1 activity was less correlated with right premotor cortex during hypnosis than during normal state. This pattern suggests a possible neural mechanism by which increases in self-monitoring processes may take control over the left-hand movements based on internal representations, derived from hypnotic suggestions and mental imagery, in place of the habitual responses to external stimuli that are normally under the guidance of premotor programs.

Modulation of Inhibitory Control and Attentional Focusing

The flexibility of human behavior is thought to be supported by executive control systems implemented in prefrontal areas, enabling us to deliberately and selectively focus our attention on currently relevant information (Shallice and Burgess, 1991; Duncan, 2001, 2006; Miller and Cohen, 2001). Consistent with models linking hypnotic phenomena with changes in executive control (Egner and Raz, 2007; Hilgard, 1974; Jamieson and Sheehan, 2004; Spiegel and Spiegel, 1978; Woody and Farvolden, 1998), our imaging data revealed significant modulations in several prefrontal regions as well as parietal regions associated with response selection and attention during hypnosis. However, different effects were observed in different frontal areas, contrasting with the normal state where these regions generally exhibited a similar pattern of activation.

In particular, the rIFG showed striking increases across all conditions during hypnosis as compared with the normal state (see Figure 3), but no selective modulation as a function of movement execution or suppression, even though this region is a key component of the ''braking circuit'' normally responsible for inhibiting prepotent or habitual actions (Aron et al., 2004b; Xue et al., 2008). Thus, rIFG activates in various conditions requiring a suppression of ongoing motor or cognitive programs (Brass et al., 2005; McNab et al., 2008), including no-go (Konishi et al., 1998; Rubia et al., 2003) or stop-signal tasks (Aron et al., 2003; Garavan et al., 1999). Consistent with these studies, we found that inhibitory processes mediated by the right IFG were recruited during NOGO trials (for both hands) in the normal state as well as during simulation of left paralysis on GO trials, indicating that feigned paralysis involves voluntary inhibitory activity in right IFG equivalent to NOGO trials. By contrast, the lack of rIFG increases during left hypnotic paralysis on GO trials, despite preserved motor activation during the preparation phase, clearly demonstrates that hypnotic effects are different from voluntary restrain and do not act through direct motor inhibition. On the other hand, the general increases in rIFG during all task conditions under hypnosis (see Figure 3) cannot be explained by an exclusive role in motor inhibition. Instead, this pattern indicates that executive control processes mediated by this region were recruited by all trial types under hypnosis, which might correspond to a state of enhanced monitoring or ''hypercontrol'' activated in response to every imperative event (GO or NOGO) in this condition. We therefore propose that IFG activity might reflect a more general self-monitoring function, or more general changes in controlling attention and responses to external stimuli, allowing internal mental representations generated through the hypnotic suggestion to guide motor behavior (perhaps via enhanced influences from precuneus), rather than simply interrupting motor outputs for prepared actions.

A distinct region in the right post-MFG might be more directly involved in the cancellation of prepared movements, as it showed

selective activation both to NOGO stimuli in the normal state (with either hand) and to L-GO stimuli during hypnotic paralysis (see Figure 3), although it is unclear why no reliable increases were seen on NOGO trials under hypnosis. Nevertheless, a similar premotor region in post-MFG has been found to activate in several motor selection tasks and is suspected to have a major a role for abstract stimulus-response representations, allowing flexible adjustments of behavior to changing task contingencies (Brass et al., 2005; Chikazoe et al., 2008). MFG thus appears to have a different function than purely inhibitory control, unlike more anterior prefrontal regions in right IFG or medial areas in ACC (Chikazoe et al., 2008; Downar et al., 2001). Therefore, changes in MFG activity might reflect the formation of different task-relevant motor representations during hypnosis as compared with normal conditions. Alternatively, MFG activation might accord with previous suggestions that some premotor areas have a specific role to produce negative motor phenomena (Luders et al., 1985). Hence, we hypothesize that MFG activity might be primarily driven by the right IFG in the normal state when inhibiting prepared movements, while the same region might be recruited through other mechanisms in order to suppress movements with the paralyzed hand during hypnosis.

The pattern of activation in left IFG was found to correspond to conditions that were behaviorally most relevant or deviant (NOGO versus GO irrespective of hand in normal state, but left versus right hand irrespective of motor response under hypnosis), and thus appeared to match the specific task demands associated with the different states. This pattern is consistent with the notion that left-sided brain areas within executive control networks play a key role in implementing task settings (Aron et al., 2004a) and/or selecting appropriate responses among competing options based on current context (Koechlin et al., 2003; Simons et al., 2005). Since left ventrolateral prefrontal areas are also recruited during learning of new associations between visual cues and motor responses (Passingham et al., 2000), their recruitment during hypnosis might reflect the maintenance of new action rules imposed by the hypnotic suggestion. This reconfiguration of activity across bilateral prefrontal areas suggests a switch in behavioral control settings, from an execution/inhibition scheme in the normal state to a left/right hand scheme under hypnosis (Fiebach and Schubotz, 2006).

Additionally, parietal regions are also known to be implicated in attentional control (Corbetta and Shulman, 2002; Raz, 2004). Together with the rIFG, the right IPL is normally activated by various inhibition tasks (Garavan et al., 1999, 2002; Langenecker and Nielson, 2003; Liddle et al., 2001; Peterson et al., 2002; Rubia et al., 2001; Sylvester et al., 2003) as well as by exogenous orienting to unexpected or rare events (Corbetta and Shulman, 2002; Kirino et al., 2000; Marois et al., 2000). Whereas the differential responses to NOGO versus GO trials were abolished in right IPL during hypnosis, just like in rIFG, these changes involved a general decrease of activity across all conditions, unlike the general increase observed in rIFG (see Figure 3). This relatively "silent" pattern in rIPL suggests that hypnosis induced a state in which attention was not differentially engaged by imperative signals, consistent with an attenuation of the normal responses to external stimuli. Furthermore, this opposite pattern of decreases in IPL with increases in IFG across all trial types reveals a striking dissociation between two highly interconnected regions within attentional networks (Corbetta et al., 2008; Fox et al., 2006) under hypnosis. We suggest that such a state of enhanced self-monitoring coupled with a partial suppression of responsiveness to external stimulation might contribute to the subjective experience of a "hidden observer" or "dissociated self" that is commonly reported under hypnosis (Hilgard, 1974).

Conclusion

By investigating mechanisms of hypnotic paralysis, our study goes beyond previous imaging studies that focused on pain perception and modulation of ACC by attentional factors during hypnosis (Egner et al., 2005; Rainville et al., 1997; Raz et al., 2005). We demonstrate that hypnosis induces the control of action by internal representations generated through suggestion and imagery, mediated by precuneus activity, and reconfigures the executive control of the task implemented by frontal lobes. These findings make an important new step toward establishing neurobiological foundations for the striking impact of hypnosis on mind and behavior.

EXPERIMENTAL PROCEDURES

Participants

Eighteen healthy subjects volunteered to participate in the study. They had no past neurological or psychiatric disease and normal or corrected-to-normal vision. These participants were selected to be highly hypnotizable, first by screening with the Harvard Group Scale of Hypnotic Susceptibility: Form A (HGSHS: A [Shor and Orne, 1963]) during a group session, and then by giving the Stanford Hypnotic Susceptibility Scale: Form C (SHSS: C) during a second individual session. Scores ranged from 9 to 12 on these two scales. In this second session, each participant was given a hypnotic suggestion while being exposed to a mock scanner noise condition and instructed to rate the depth of hypnosis on a 1-to-10 scale at several times during the session.

Stimuli

Visual stimuli included three iso-luminant pictures of hands (one grayscale, one green, and one red), which depicted either a right or left (mirrored) hand as seen from a dorsal view (palm down). All images were projected on a screen and reflected on a mirror mounted on the MRI head coil, with a size of $\sim 6^{\circ} \times 6^{\circ}$ visual angle.

Procedure

All participants performed a modified go-nogo task using both hands. Each trial began with a fixation cross of 500 ms, followed by a preparation cue (PREP condition) represented by a grayscale picture of a hand (right or left), indicating on which side to prepare the upcoming movement. After a varying interval between 1 to 5 s, the hand picture could turn to either green or red (for 750 ms): when green, participants had to respond as quickly as possible by pressing a button with the corresponding hand (GO condition, 75% of trials); but when red, the prepared movement had to be withheld (NOGO condition, 25% of trials). A visual feedback was given on all trials after a random interval of 100–800 ms (signaling correct, incorrect, or no response detected). All conditions were presented in blocks of 100 trials (in pseudorandomized order), separated by a 30 s rest period at the middle of each block.

Twelve participants performed the experiment in a normal state for two consecutive blocks and in a hypnotic state for two other consecutive blocks (order counterbalanced). During hypnosis, subjects received a suggestion that their left hand was paralyzed, prior to performing the task. The hypnotic induction took place in the MRI scanner and was given by an experienced clinician (A.F.) via a microphone from the MRI control room. Participants were first instructed to close their eyes and relax, they received a suggestion that their left hand became heavy, stiff, and progressively unable to move. Once they

were deeply absorbed, they were asked to open their eyes and rate their level of hypnosis, as previously trained in the prescanning session. Functional MRI acquisition started only if ratings were ≥ 6 (on a 1-to-10 scale). Halfway in each block, the task was interrupted for 30 s (without stopping fMRI acquisition), while the suggestion was consolidated and a new subjective rating was obtained from the participant (in the hypnotic state), or a neutral encouragement was given and a verbal self-report about performance was made via the microphone (in the normal state). These ratings confirmed a reliable level of hypnosis (≥ 5) throughout scanning in all cases. The upper face and hands of participants were continuously monitored by an infrared eye-tracker (ASL LRO 450) and an MRI-compatible video camera (Philips Medical Systems), respectively.

Six different participants performed the same task with the instruction to simulate that their left hand was paralyzed (two blocks). After being told that they served as controls for a study of stroke patient with hemiplegia, they were asked to act "as if" they were suffering from motor weakness and unable to move their fingers. The rest of the procedure was exactly as above.

Prior to fMRI, all participants performed the task for a short training block of 20–30 trials.

fMRI Acquisition and Analysis

MRI data were acquired on a 1.5T whole-body INTERA system (Philips Medical Systems), using the standard head-coil configuration. For each participant, structural images were acquired with a 3D-GRE T1-weighted sequence (FOV = 250 mm, TR/TE/Flip = 15 ms/5.0 ms/30°, matrix = 256 × 256, slice-thickness = 1.25 mm); and functional images with a GRE EPI sequence (TR/TE/Flip = 2500 ms/40 ms/80°, FOV = 250 mm, matrix = 128 × 128). Each functional image comprised 32 contiguous 3.4 mm axial slices (TR = 2.5 s) oriented parallel to the inferior edge of the occipital and temporal lobes. For each of the four experimental blocks, a total of 266 functional images were acquired continuously.

Functional images were analyzed using the general linear model (Friston et al., 1998) for event-related designs in SPM2 (Wellcome Department of Imaging Neuroscience, London, UK; http://www.fil.ion.ucl.ac.uk/spm). All images were realigned, corrected for slice timing, normalized to an EPI-template (resampled voxel size of 3 mm), spatially smoothed (8 mm FWHM Gaussian kernel), and high-pass filtered (cutoff 120 s).

Statistical analyses were performed on a voxelwise basis across the whole-brain. Individual events were modeled by a standard synthetic hemodynamic response function (HRF). To account for residual movement artifacts after realignment, movement parameters derived from realignment corrections (three translations, three rotations) were entered as covariates of no interest. Trials with errors were not included in the analysis of fMRI data. The general linear model was then used to generate parameter estimates of activity at each voxel (betas), for each experimental condition (PREP, GO, and NOGO, for both hands), resulting in six regressors for each run (L-PREP, R-PREP, L-GO, R-GO, L-NOGO, R-NOGO) in each participant. Statistical parametric maps were generated from linear contrasts between the HRF betas for the different conditions. Contrasts comparing the main effects of state were obtained by standard t tests between the normal versus hypnotic runs for a given task condition (e.g., NORMAL L-GO versus HYPNO L-GO).

A random-effect group analysis was then conducted on contrast images from the individual analyses, using one-sample t tests across the whole brain (Friston et al., 1998). As standard practice, focal activations were considered as significant at a voxel level of $p < 0.001$ (uncorrected) with a cluster threshold of more than 20 voxels, unless reported otherwise. In addition, post-hoc analyses were performed on selected regions of interest (i.e., to compare two conditions for a cluster identified in a main contrast pooling across these conditions) by using t test contrasts on the peak of activation defined by a previous contrast and searching for the z score maxima within a 10 mm sphere in SPM. ANOVAs and t tests were also performed on average betas extracted from selected regions of interest (previously defined in SPM), using standard statistics in SPSS 15.0 (SPSS Inc., Chicago, IL, USA). Repeated-measure ANOVA was used for comparisons between hypnosis and normal state (within-group statistics), whereas nonrepeated ANOVAs were used for between simulation and normal state (between-group).

For functional connectivity analysis, we first selected the peak of activity in right motor cortex (M1, seed region) based on the results found for GO trials in normal state (L-GO > L-NOGO), using a new GLM model with the signal from a sphere of 6 mm centered on the rM1 as an additional regressor. Thus, this new design matrix included four runs that each contained six regressors for the six conditions (see above), plus one regressor for the time series of rM1 activity (nonconvolved with the HRF), as well as six regressors for the movement realignment parameters, and one regressor for the constant session effect in each run. We then contrasted the rM1 regressors of the two normal state runs to the same regressors of the hypnotic state, using a paired t test across the whole brain for each subject (with a threshold of $p < 0.001$ uncorrected and cluster extent of five voxels). A random-effect group analysis was conducted on these individual contrast images. A similar analysis was performed with a seed in left M1. Finally, we conducted the same analysis for the simulation group and then compared the degree of connectivity of rM1 in this group with the normal state by using t tests on the average betas of connectivity extracted from the relevant regions of interest.

Behavioral data were analyzed with Microsoft Excel and SPSS.

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