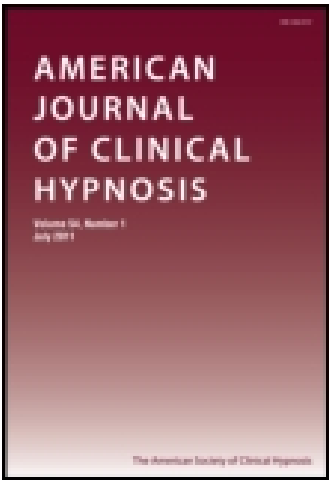

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Hypnosis and Imaging of the Living Human Brain

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Hypnosis and Imaging of the Living Human Brain

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Over more than two decades, studies using imaging techniques of the living human brain have begun to explore the neural correlates of hypnosis. The collective findings provide a gripping, albeit preliminary, account of the underlying neurobiological mechanisms involved in hypnotic phenomena. While substantial advances lend support to different hypotheses pertaining to hypnotic modulation of attention, control, and monitoring processes, the complex interactions among the many mediating variables largely hinder our ability to isolate robust commonalities across studies. The present account presents a critical integrative synthesis of neuroimaging studies targeting hypnosis as a function of suggestion. Specifically, hypnotic induction without task-specific suggestion is examined, as well as suggestions concerning sensation and perception, memory, and ideomotor response. The importance of carefully designed experiments is highlighted to better tease apart the neural correlates that subserve hypnotic phenomena. Moreover, converging findings intimate that hypnotic suggestions seem to induce specific neural patterns. These observations propose that suggestions may have the ability to target focal brain networks. Drawing on evidence spanning several technological modalities, neuroimaging studies of hypnosis pave the road to a more scientific understanding of a dramatic, yet largely evasive, domain of human behavior.

Keywords: functional magnetic resonance imaging, hypnosis, neuroimaging, positron emission tomography

While developments in neuroimaging techniques continue to flourish, imaging studies of hypnosis have yet to deliver convincing evidence that would inform a reliable neurobiological theory of hypnosis (Halligan & Oakley, 2013; Jamieson, 2007; Kihlstrom, 2013; Oakley & Halligan, 2009, 2013; Raz & Shapiro, 2002). Here we review relevant neuroimaging studies to appraise current opinions concerning the neurobiological underpinnings of hypnosis. Our goal is twofold: (1) to identify the relative merits and drawbacks of neuroimaging studies concerning hypnosis and (2) to offer an integrative synthesis of neuroimaging findings and how they relate to theoretical models of hypnosis (see Table 1).

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TABLE 1
List of Neuroimaging Studies of Hypnosis

Study	*Imaging technique*	*Hypnosis conditions*	*Experiment*
Hypnotic induction without task-specific suggestion:			
Maquet et al. (1999)	Positron emission tomography (PET)	Highly hypnotic-susceptible individuals (HHSs) only; normal alertness versus hypnosis	Hypnotic induction with minimal suggestions and hypnotic induction with suggestions to induce visual hallucinations; comparisons of (1) normal alertness while participants listen to pleasant autobiographical events, (2) hypnotic induction + suggestions to re-experience pleasant autobiographical memories; and (3) hypnotic induction + suggestions for color hallucinations
Faymonville et al. (2000)	PET	HHSs only; normal alertness versus hypnosis	Noxious and non-noxious stimulations during (1) normal alertness, (2) mental imagery, and (3) following induction in which participants re-experience pleasant autobiographical memories
Rainville, Hofbauer, Bushnell, Duncan, and Price (2002)	PET	Normal alertness versus hypnosis	Mental relaxation and mental absorption before and after hypnotic induction
Faymonville et al. (2003)	PET	HHSs only; normal alertness versus hypnosis	Comparison of noxious and non-noxious stimulations during (1) normal alertness, (2) mental imagery, and (3) following hypnotic induction
Schulz-Stübner et al. (2004)	Functional magnetic resonance imaging (fMRI)	Normal alertness versus hypnosis	Comparison of normal alertness and hypnotic induction during repeated noxious stimulations
Egner, Jamieson, and Gruzelier (2005)	fMRI–electroencephalography (EEG)	Low hypnotic-susceptible individuals (LHSs) versus HHSs; normal alertness versus hypnosis	Comparison of neural activity in the anterior cingulate cortex (ACC) and the dorsal lateral prefrontal cortex (DFPFC) during Stroop task as a function of (1) susceptibility to hypnosis (HHSs versus LHSs) and (2) hypnotic conditions (normal alertness versus hypnotic induction)
Vanhaudenhuyse et al. (2009)	fMRI	HHSs only; normal alertness versus hypnosis	Noxious stimulations during normal alertness and following hypnotic induction
McGeown, Mazzoni, Venneri, and Kirsch (2009)	fMRI	LHSs versus HHSs; normal alertness versus hypnosis	fMRI resting state of HHSs and LHSs in normal alertness and following hypnotic induction during two experimental conditions: rest versus visual task
Demertzi et al. (2011)	fMRI	HHSs only; normal alertness versus control condition versus hypnosis	fMRI resting state of (1) normal alertness, (2) following hypnotic induction, and (3) during a control condition of autobiographical mental imagery

Müller, Bacht, Schramm, and Seitz (2012)	fMRI	HHSs only; normal alertness versus hypnosis	Comparison between actual and imagined repetitive finger movements following hypnotic induction in (1) normal alertness and (2) hypnosis
Deeley et al. (2012)	fMRI	HHSs only; correlation between hypnotic depth and brain activity	Resting state of (1) prehypnosis, (2) hypnotic induction, and (3) posthypnosis
Müller, Bacht, Prochnow, Schramm, and Seitz (2013)	fMRI	HHSs only; normal alertness versus hypnosis	Comparison of actual and imagined repetitive finger movements in (1) normal alertness and (2) following a hypnotic induction
Sensation and perception:			
Rainville, Duncan, Price, Carrier, and Bushnell (1997)	PET	Normal alertness versus hypnotic induction without task-specific suggestion versus hypnotic induction + suggestions	During noxious stimulations, comparison of (1) normal alertness, (2) hypnotic induction without pain-related suggestions, (3) hypnotic induction + suggestions to increase pain unpleasantness, and (4) hypnotic induction + suggestions to decrease pain unpleasantness
Szechtman, Woody, Bowers, and Nahmias (1998)	PET	HHSs only: hypnotic "hallucinators" versus "non-hallucinators"; normal alertness versus control condition versus hypnosis	Comparisons of HHSs and LHSs in (1) normal alertness, (2) listening to a tape message, (3) imagining the tape message, and (4) hypnotic hallucination of the tape message
Wik, Fischer, Bragée, Finer, and Fredrikson (1999)	PET	Fibromyalgia patients; normal alertness versus hypnosis	Comparison of normal alertness and hypnotic hypoalgesia in fibromyalgia patients
Rainville, Carrier, Hofbauer, Bushnell, and Duncan (1999)	PET	Normal alertness versus hypnotic induction versus hypnotic modulation of pain perception	Noxious stimulations in (1) normal alertness, (2) following hypnotic induction, and (3) following hypnotic induction + suggestions for altered pain experience
Kosslyn, Thompson, Costantini-Ferrando, Alpert, and Spiegel (2000)	PET	HHSs only; normal alertness versus hypnosis	Hypnotic altered perception of colors; normal alertness versus hypnotic induction of the following conditions: (1) correct perception of a colorful stimulus, (2) suggestions to drain colors from a colorful stimulus, (3) correct perception of a grayscale stimulus, and (4) suggestions to add colors to a grayscale stimulus
Hofbauer, Rainville, Duncan, and Bushnell (2001)	PET	Normal alertness versus hypnotic induction versus hypnotic modulation of pain perception	Noxious and non-noxious stimulations under (1) normal alertness, (2) following hypnotic induction, (3) following hypnotic induction + hypnotic suggestions for increased pain intensity, and (4) following hypnotic induction + suggestions for decreased pain intensity
Derbyshire, Whalley, Stenger, and Oakley (2004)	fMRI	HHSs only; noxious stimulation versus imagined pain perception versus hypnotically induced pain	Comparisons of (1) noxious stimulation, (2) imagined pain, and (3) hypnotically induced pain

(*Continued*)

TABLE 1
(Continued)

Study	Imaging technique	Hypnosis conditions	Experiment
Raz, Fan, and Posner (2005a)	fMRI–EEG	LHSs versus HHSs	HHSs and LHSs performed the Stroop task with and without a posthypnotic suggestion to view words as nonsense strings
Raij, Numminen, Narvanen, Hiltunen, and Hari (2005)	fMRI	HHSs only; normal alertness versus hypnotic induction versus hypnotically induced pain	HHSs rated the reality of pain under (1) noxious stimulations and (2) hypnotic hallucination for pain perception
Röder et al. (2007)	fMRI	HHSs only; normal alertness versus hypnotic relaxation versus hypnotic depersonalization	Noxious stimulations during (1) normal alertness, (2) hypnotic relaxation, (3) hypnotic depersonalization (i.e., suggestions to experience detached self from the body)
Raij, Numminen, Närvänen, Hiltunen, and Hari (2009)	fMRI	HHSs only; hypnotic induction versus hypnotically induced pain	Hypnotic induction (i.e., baseline) versus hypnotically induced pain
Derbyshire, Whalley, and Oakley (2009)	fMRI	Fibromyalgia patients (good hypnotic responder); normal alertness versus hypnosis	In fibromyalgia patients, suggestions for hyperalgesia and suggestions for hypoalgesia in (1) normal alertness and (2) following hypnotic induction
Nusbaum et al. (2010)	PET	Patients with chronic back pain; normal alertness versus hypnosis	In patients with chronic low-back pain, comparison of direct suggestions for analgesia (i.e., directly referring to pain location and pain relief) and indirect suggestions for analgesia (i.e., referring to general well-being) in (1) normal alertness and (2) following hypnotic induction
Abrahamsen et al. (2010)	fMRI	Patients with temporomandibular disorder; normal alertness versus hypnosis	Noxious stimulations in patients with temporomandibular disorder during (1) normal alertness, (2) hypnotic hypoalgesia, and (3) hypnotic hyperalgesia
McGeown et al. (2012)	fMRI	LHSs versus LHSs; normal alertness versus hypnosis; suggestion versus non-suggestion	Suggestions to add colors to a grayscale stimulus and suggestions to drain colors from a colorful stimulus between (1) HHSs and LHSs and (2) in normal alertness and following an induction
Ludwig et al. (2013)	fMRI	Normal alertness versus hypnosis	Comparison of (1) posthypnotic suggestions to reduce food valence and (2) reduction of food valence via colors associated autosuggestions during a bidding task
Memory:			
Mendelsohn, Chalamish, Solomonovich, and Dudai (2008)	fMRI	Participants susceptible to posthypnotic amnesia (PHA) versus PHA control group	Investigation of PHA in (1) HHSs compared to LHSs for (2) episodic versus source memory during (3) PHA versus correct recall of memories with a posthypnotic cue

Ideomotor action:			
Halligan, Athwal, Oakley, and Frackowiak (2000)	PET	Single case study; no movement versus four experimental conditions	Hypnotic paralysis in a control condition (i.e., no movement) versus four experimental conditions following hypnotic induction and suggestion for left leg paralysis: (1) moving right leg, (2) attempting to move right leg, (3) moving left leg, and (4) attempting to move left leg
Ward, Oakley, Frackowiak, and Halligan (2003)	PET	HHSs only; simulated paralysis versus hypnotic paralysis	Comparison of two paralysis conditions following hypnotic induction: (1) hypnotic left leg paralysis versus (2) simulated paralysis
Blakemore, Oakley, and Frith (2003)	PET	HHSs only; rest versus active movement versus passive movement versus suggestion for passive movement	Alteration of the sense of agency; following hypnotic induction, comparisons of (1) rest, (2) real active movement (i.e., self-generated movement correctly attributed to the self), (3) real passive movement (i.e., externally generated movement correctly attributed to an external cause), and (4) deluded passive movement (i.e., self-generated movement incorrectly attributed to an external cause via hypnotic suggestion)
Cojan et al. (2009)	fMRI	HHSs only; normal alertness versus simulated paralysis versus hypnotic paralysis	Go/NoGo task under (1) normal alertness, (2) hypnotic left-hand paralysis, and (3) feigned paralysis
Pyka et al. (2011)	fMRI	HHSs only; normal alertness versus hypnotic paralysis	fMRI resting state of (1) normal alertness and (2) hypnotically induced ideomotor paralysis
Deeley et al. (2013a)	fMRI	HHSs only; hypnotic induction versus hypnotic induction + suggestion for paralysis	Left and right upper limb movements following (1) hypnotic induction versus (2) attempted movement following hypnotic paralysis
Deeley et al. (2013b)	fMRI	HHSs only; normal alertness versus hypnotic experimental conditions	Altered sense of agency and awareness of movement; comparison of movement under (1) normal alertness, (2) hypnotic voluntary movement, (3) hypnotic involuntary movement + awareness of movement, and (4) hypnotic involuntary movement + reduced awareness of movement

(*Continued*)

TABLE 1
(Continued)

Study	*Imaging technique*	*Hypnosis conditions*	*Experiment*
Burgmer et al. (2013)	fMRI	HHSs only; normal alertness versus hypnotic paralysis	Comparison of imitation and observation of movements in (1) normal alertness and (2) following hypnotically induced ideomotor paralysis
Deeley et al. (2014)	fMRI	HHSs only; normal alertness versus hypnotic alteration of the sense of agency and locus of control	Modulations of locus of control and sense of agency within different experimental conditions: (1) voluntary movements in normal alertness, (2) voluntary movements following induction, (3) induction + suggestions for external and impersonal alien control of movements, (4) induction + suggestions for external and personal alien control of movements, and (5) induction + suggestions for internal and personal alien control of movements

Neuroimaging studies often operationalize hypnosis through induction and suggestions procedures. This approach raises concerns as to whether experimental findings generalize to clinical contexts. However, researchers train participants prior to experiments and confirm the effects of induction via self-report, thereby supporting the "ecological validity" of hypnosis in the laboratory (Oakley, Deeley, & Halligan, 2007).

The Challenge of Neuroimaging Hypnotic Phenomena

The advent of brain-imaging technology captures the imagination of the masses (Ali, Lifzhitz, & Raz, 2014; Choudhury & Slaby, 2011; Jones & Mendell, 1999). These technological advances generate excitement and expectation in the cognitive sciences, including psychology and psychiatry (Aue, Lavelle, & Cacioppo, 2009; Axmacher, Elger, & Fell, 2009; Choudhury & Slaby, 2011; Dolan, 2008; Jones & Mendell, 1999; Kirmayer & Crafa, 2014; Malhi & Lagopoulos, 2008; Nathan, Phan, Harmer, Mehta, & Bullmore, 2014; Poldrack, 2012). This enthusiasm also applies to hypnosis research (Halligan & Oakley, 2013; Jamieson & Woody, 2007; Kihlstrom, 2013; Oakley & Halligan, 2009, 2013). However, after nearly two decades of imaging hypnotized brains, the pursuit of a neurobiological model based on neuroimaging remains inconclusive (Kirmayer & Crafa, 2014; Macdonald & Raz, 2014; Raz & Macdonald, 2014, 2015).

Imaging the brain imposes a wealth of practical and theoretical restrictions that confine the scope of investigation. These limitations include, for example, burdening participants with unnatural testing environment and ecologically invalid postures (Raz et al., 2005b; Thibault, Lifshitz, Jones, & Raz, 2014), the temporal and spatial resolution of (e.g., fMRI) scanners (Axmacher et al., 2009), and the capacity to detect meaningful signals amid background noise (Filippi, 2009). However, hypnotic effects seem to largely transcend these caveats and ecological barriers (Oakley et al., 2007).

Neuroimaging entails specific challenges to the study of hypnosis. For example, hypnosis typically encompasses an induction procedure, designed to increase the hypnotic response, followed by direct suggestions to modify perception, cognition, or behavior (Kihlstrom, 2008). Despite this induction–suggestion distinction, neuroimaging protocols provide little means to differentiate between the effects of hypnotic induction and the effects of hypnotic suggestions (Cardeña, Jönsson, Terhune, & Marcusson-Clavertz, 2013; Mazzoni, Venneri, McGeown, & Kirsch, 2013). The instructions during the induction procedure already represent some form of suggestion (Gandhi & Oakley, 2005). Some researchers attempt to resolve this concern by inducing a so-called *neutral* plane of hypnosis using an induction with minimal suggestions (Cardeña et al., 2013; Kihlstrom & Edmonston, 1971; Mazzoni et al., 2013). Yet, the use of suggestions appears inevitable, thereby undermining the notion of a suggestion-free induction. Studies may partially circumvent this central issue by keeping the task and suggestions constant across hypnotic conditions, thereby allowing participants to receive identical suggestions while performing the same task under hypnosis and normal alertness. However, isolating effects pertaining to the induction procedure from those pertaining to suggestions represents a constant challenge for neuroimaging studies addressing hypnosis.

A high level of inter-individual variability in susceptibility to suggestions impacts both practical and theoretical aspects of hypnosis research (Carli, Manzoni, & Santarcangelo, 2008; Heap, Brown, & Oakley, 2004; Laurence, Beaulieu-Prévost, & Du Chéné, 2008; Piccione, Hilgard, & Zimbardo, 1989; Terhune, Cardeña, & Lindgren, 2011). To account for this variability, studies often compare the effects elicited by HHSs with those elicited by LHSs (Nash & Barnier, 2008). As it turns out, HHSs use various cognitive strategies to comply with hypnotic suggestions (Barnier, Cox, & McConkey, 2014; McConkey & Barnier, 2004; McConkey, Glisky, & Kihlstrom, 1989; Nash & Barnier, 2008). The principle of equifinality (i.e., this principle states that different means can lead to the same end state) therefore applies to hypnotic response, whereby similar hypnotic responses may rely on different cognitive routes (Cardeña, 2014a). This situation further contributes to the inherent heterogeneity of hypnotic phenomena. The fact that numerous hypnotic effects surface only in subjective reports also exacerbates this concern (Kihlstrom, 2008). Thus, individual differences reduce our ability to precisely sequester commonalities among disparate studies.

Discerning hypnotic-related from task-related effects represents another important challenge. For example, both the Stroop task and hypnosis relate to modulations of the ACC, making it difficult to separate hypnotic from Stroop effects (Egner et al., 2005; Raz, Fan, & Posner, 2005a). Subsequently, a meaningful study that includes an experimental task requires a control condition to differentiate hypnotic from task effects.

Most neuroimaging studies involving hypnosis either focus on hypnotic phenomena or use hypnosis as an experimental instrument to investigate (a)typical cognition (Bortolotti, Cox, & Barnier, 2012; Cox & Barnier, 2010; Oakley & Halligan, 2009, 2013). Due to their different aims, intrinsic and instrumental hypnosis seldom combine in the same study (Barnier, 2002; Oakley & Halligan, 2009). Together, all of the above-mentioned concerns constrain our ability to build a reliable neurobiological theory of hypnosis.

Careful experimentation represents the primary solution to collect reliable neuroimaging data (Filippi, 2009). Moreover, combining evidence from different methods makes for a good strategy to test and support experimental hypotheses (Henson, 2005, 2006). In the specific context of hypnosis, adopting a two-by-two design crossing hypnosis and suggestion as a function of hypnotic susceptibility embodies the prime strategy for teasing apart the effects of hypnosis (see Figure 1; Mazzoni et al., 2013; Oakley & Halligan, 2010). This matrix ascertains the effects of key variables that influence hypnotic phenomena. Alas, in light of practical and financial limitations, most research groups rarely follow this template. Instead, they rely on imaging of specific hypnotic phenomena, often with a single control condition.

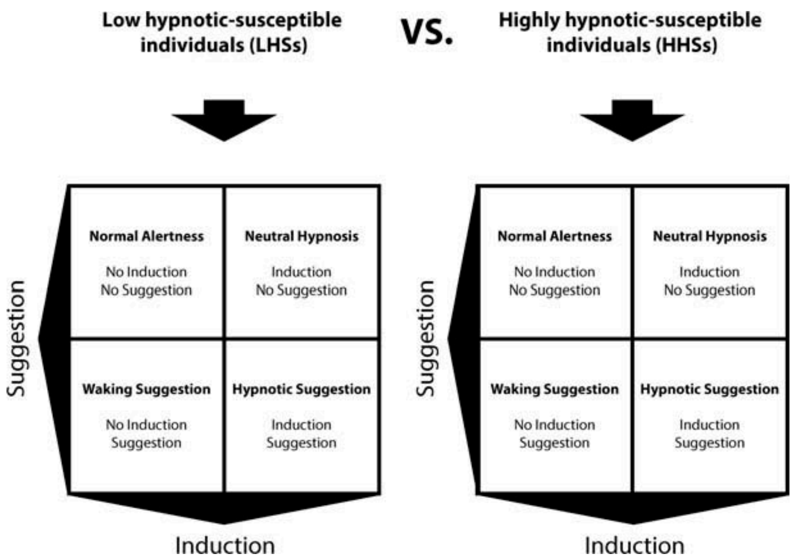

FIGURE 1 Balanced experimental design to investigate hypnotic phenomena allows researchers to tease apart sources of effects (cf., Mazzoni et al., 2013).

In this article we examine most of the available research concerning neuroimaging and hypnosis. We categorize studies as a function of suggestions and complement a recent review that focused on converging themes across imaging studies (Casale et al., 2012). Thus, we provide an overarching approach to the brain mechanisms likely engaged by suggestion. Our framework aims to target meaningful differences and pinpoint areas of intersection across studies, paradigms, and subdomains of specialty.

Some hypnosis scholars have taken on the thankless challenge of defining hypnosis (Wagstaff, 2014). These efforts, perhaps unintentionally, seem to have been largely focused on making their devotions at the wrong altar (Cardeña, 2014b; Connors, 2014; Kirsch, 2014; Laurence, 2014; O'Neil, 2014; Polito, Barnier, & McConkey, 2014; Terhune, 2014; Woody & Sadler, 2014). Debates concerning the nature of hypnosis, albeit most definitions cluster around state versus non-state views, are central to this challenge (Kihlstrom, 1985; Kirsch et al., 2011; Wagstaff, 1998). Despite relative uncertainties concerning the ontological status of hypnotic phenomena, current conceptions propose valuable hypotheses spanning the behavioral, cognitive, subjective, and neurobiological domains of hypnosis (Nash & Barnier, 2008). Here we focus, therefore, on how neuroimaging findings shape and construe these current definitional frameworks (Raz, 2011a).

Culling of Neuroimaging Findings

Method

We searched for neuroimaging studies of hypnosis using combinations of the following key words in Google Scholar, PubMed, and PsycINFO: hypnosis, neuroimaging, fMRI, and PET. Because we aim to localize and frame the underlying neural mechanisms of hypnosis across very similar methodologies, our review solely includes fMRI and PET, therefore excluding EEG, magnetoencephalography, near-infrared spectroscopy, and structural or volumetric imaging studies. We included 37 neuroimaging studies. We excluded studies that did not use imaging of at least one experimental condition of hypnotic induction or hypnotic response. We also excluded three studies that did not provide or provided only vague indications concerning the induction procedure. Table 1 provides a brief summary of the method and results for each study. In the first section of this article, we describe the studies that used hypnotic induction but did not use subsequent task-specific hypnotic suggestions. Suggestions in these studies are either indirect or unspecified in connection with the task. We describe studies that investigated hypnotic suggestions that focus on sensation and perception, memory, and ideomotor action. These studies highlight how hypnotic suggestions can elicit changes in focal brain areas. Overall, the findings support the idea that hypnosis engages brain areas related to attention, cognitive control, and monitoring.

Hypnotic Induction Without Task-Specific Suggestion

Hypnotic induction without task-specific or indirect suggestions mainly engages the frontal and the thalamic areas (see Figure 2). These observations are consistent across various experimental contexts, including mental imagining, the Stroop task, administration of noxious stimulations, as well as in neurophenomenological and resting state studies (Deeley et al., 2012; Demertzi et al., 2011; Egner et al., 2005; Faymonville et al., 2000, 2003; McGeown et al., 2009; Müller et al., 2012, 2013; Rainville et al., 2002; Vanhaudenhuyse et al., 2009).

Induction often yields profound feelings of relaxation and absorption (Rainville et al., 2002; Rainville & Price, 2003; Wagstaff, 2014). This paradoxical mental state of relaxed yet intense attention focus putatively subserves various hypnotic experiences (Cardeña, 2014a). At the neural level, neuroimaging results show that these phenomenological changes correspond to complex thalamocortical dynamics that chiefly index regulation of alertness and attention processing (Rainville et al., 2002). Consistent with this view, modulations of the right inferior parietal area corroborate the involvement of the frontoparietal attention network. Supplementing these findings and further demonstrating the effect of hypnotic induction over the thalamocortical alerting network (Posner &

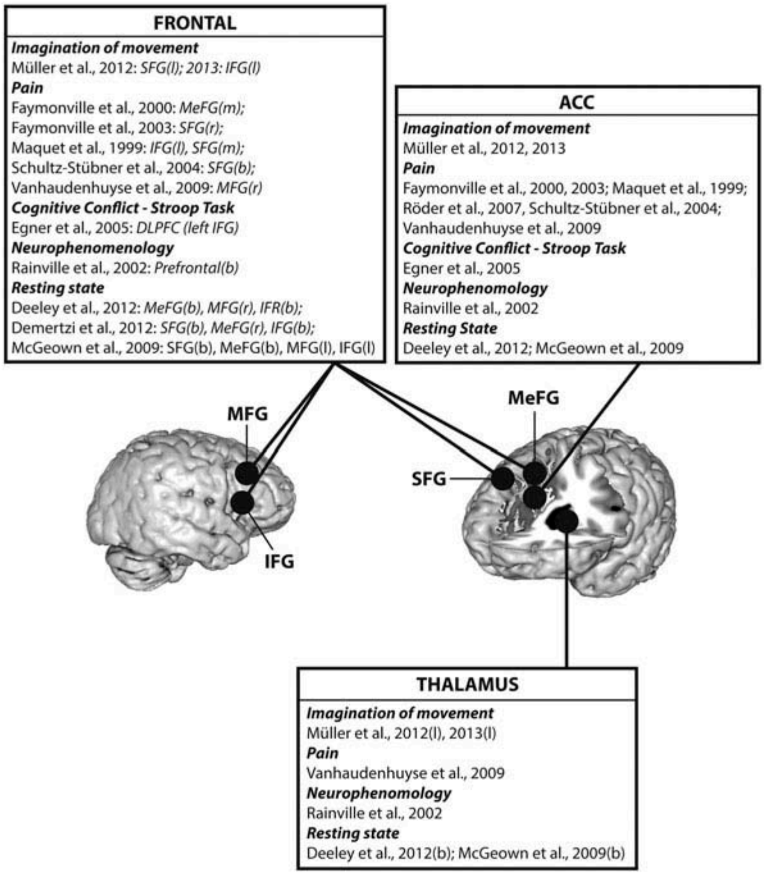

FIGURE 2 Brain regions related to hypnotic induction without task-specific suggestions (SFG: superior frontal gyrus; MFG: middle frontal gyrus; IFG: inferior frontal gyrus; MeFG: medial frontal gyrus; laterality: “r” for right, “l” for left, and “b” for bilateral).

Petersen, 1990; Raz & Buhle, 2006), additional studies report hypnotic modulations of the thalamic area (Deeley et al., 2012; Faymonville et al., 2003; McGeown et al., 2009; Müller et al., 2012, 2013; Rainville et al., 2002; Vanhaudenhuyse et al., 2009). These collective results reveal that hypnotized individuals conform to the directives of an induction by engaging mental relaxation and absorption. Moreover, they highlight the top-down, versus bottom-up, nature of hypnosis (Raz, 2011b).

Evidence from resting-state studies of hypnosis also reveals the engagement of attention (Deeley et al., 2012; McGeown et al., 2009). Resting states represent recordings of spontaneous cerebral interactions between various regions in the absence of task-directed activities (Fox & Raichle, 2007). Using this approach, two independent research groups established that (1) hypnotic inductions link to a substantial activity decrease in the default-mode network (DMN), a brain network typically related to the spontaneous generation of cognition (Buckner, Andrews-Hanna, & Schacter, 2008), and (2) increased activity in the frontoparietal attention network (Deeley et al., 2012; McGeown et al., 2009). These opposing neural patterns between DMN and the attention network likely account for negatively correlated interactions (Fox et al., 2005). These findings propose that induction procedures instigate a marked reduction in the production of cognition, as indexed by the disengagement of the DMN as well as a discernible increase in absorption, manifest by the activation of the frontoparietal attention network (cf., Demertzi et al., 2011).

Beyond changes in processing of attention, dissociation theorists argue that hypnosis decouples control and monitoring processes (Woody & Farvolden, 1998; Woody & Sadler, 2008). A pivotal combined fMRI–EEG study tested this idea by investigating neural activity in the Stroop task following hypnotic induction without a task-specific suggestion (Egner et al., 2005). Considered one of the gold standards to measure executive attention during cognitive conflict (MacLeod, 1991), the Stroop task provides the means to appropriately examine control and monitoring processes. Supporting the dissociation hypothesis, results revealed distinct profiles of activation for the dorsolateral prefrontal cortex (DLPFC), a brain region associated with attention and cognitive control (Corbetta, Patel, & Shulman, 2008; Nee et al., 2013) and the ACC—a key node in cognitive monitoring (Botvinick, 2007; Botvinick, Cohen, & Carter, 2004; Shenhav, Botvinick, & Cohen, 2013). These distinct activation profiles emerged as a function of hypnotic trait (HHSs versus LHSs) and hypnotic conditions (hypnosis versus baseline). Specifically, for HHSs under hypnosis, elevated ACC activity reflected the online detection of a cognitive conflict, whereas the DLPFC showed little, if any, modulation. This subpar detection of cognitive control supports the idea that hypnotic induction may decouple conflict from monitoring. Poor behavioral performance on task following induction further supports this interpretation (Egner & Raz, 2007).

Certain investigations concerning the perception of pain report hypnoanalgesia despite the absence of direct analgesic suggestions. In these experiments, researchers ask participants to focus on autobiographical memories, thereby orienting their attention away from sensory inputs (Faymonville et al., 2000, 2003; Maquet et al., 1999; Vanhaudenhuyse et al., 2009). Hence, inattention to noxious stimulus seems central to this hypnotic phenomenon (Landry, Appourchaux, & Raz, 2014). According to this view, hypnoanalgesia is analogous to inattentional blindness in that a secondary attention demanding task (e.g., focusing on autobiographical memories) taxes cognitive resources, directs attention away from noxious sensations, and reduces conscious access to nociception (Kuhn & Tatler, 2011; Memmert, 2010; Moran & Brady, 2010; Most, 2010).

Current findings render unlikely the proposition that altered pain perception comes about via exclusive modulations of selection mechanisms (Faymonville, Boly, & Laureys, 2006; Pekala & Kumar, 2007). Instead, several studies report that noxious stimulation during induction without direct analgesic suggestions leads to modulation of the ACC, a central component of the pain neuromatrix (Faymonville et al., 2000; Maquet et al., 1999; Schulz-Stübner et al., 2004). One such study reports a marked reduction of ACC, thalamic, and striatal activity for matched-intensity stimulation (Vanhaudenhuyse et al., 2009). Such findings intimate that hypnosis and top-down regulation alter the conscious representation of nociception. Hypnotic modulations of the ACC, which plays a central role in the integration of negative affect, pain, and cognitive control (Shackman et al., 2011), may therefore reflect perception of nociceptive signals under altered conscious perception. Moreover, the ACC shares many neural pathways with various brain regions. Unlocking the effect of hypnosis on these various pathways, fMRI results show that hypnotic induction and indirect suggestions modify the connectivity between the ACC and several brain regions (Faymonville et al., 2003). Likewise, induction and noxious stimulation links to altered connectivity between the frontal area and the primary somatosensory cortex, a fundamental area for nociception (Vanhaudenhuyse et al., 2009). Collectively, therefore, these hypnotic changes in connectivity putatively correspond to perception under altered consciousness and reinterpretation of sensory events.

Hypnotic and Posthypnotic Suggestions

Following the exploration of studies that scrutinized neural correlates of hypnotic induction in the absence of task-specific suggestion, we now turn to studies that considered hypnotic and posthypnotic suggestions. Suggestions are communicable representations capable of transforming thoughts and actions (Halligan & Oakley, 2014). From targeted alterations of sensory processing (e.g., Raz, Kirsch, Pollard, & Nitkin-Kaner, 2006) to placebo responses (e.g., Flaten, Simonsen, & Olsen, 1999), various reports document their effects on cognition and behaviors (Michael, Garry, & Kirsch, 2012). The singularity of hypnotic and posthypnotic suggestions lies in their usage following an induction procedure. Thus, following the induction, operators provide participants with directives designed to prompt certain mental and behavioral changes (Hammond, 1990). These suggestions convey imaginative instructions to modify perception, memory, or behavioral action and compel individuals to adopt cognitive and behavioral strategies compatible with the suggested idea (Kihlstrom, 2008). Generally, suggestions promote the establishment of strategies that lead to the implementation of hypnotic responses (Halligan & Oakley, 2014; Kihlstrom, 2008; Lifshitz, Aubert Bonn, Fischer, Kashem, & Raz, 2013a; Raz et al., 2006; Raz, Shapiro, Fan, & Posner, 2002). Importantly, these responses largely feel involuntary and effortless (Spanos, Rivers, & Ross, 1977), one of the hallmarks of the hypnotic experience (Kirsch & Lynn, 1998).

Suggestions in the absence of an induction can yield comparable results to those of hypnosis (Mazzoni et al., 2009; McGeown et al., 2012; Raz et al., 2006). Consistent with these results, brain imaging of suggested altered perception of colors uncovered that, while suggestions engage the fusiform gyrus, a cortical area associated to color perception, induction hardly influences activity in this brain region (McGeown et al., 2012). In addition, compared to LHSs, HHSs display greater frontoparietal activity in response to suggestions, possibly alluding to a specific neural pattern during the implementation of responses. These observations seem to imply that suggestions, on their own, engage specific brain regions relevant to hypnotic response. Furthermore, this line of reasoning arguably intimates that the frontal activation in response to suggestion represents a core neurocognitive component of hypnotic phenomena (Egner & Raz, 2007). The functional role of hypnotic induction was also questioned, deeming it an instrumental facilitator to hypnotic response rather than a prerequisite (Kirsch & Lynn, 1995; Lynn, Kirsch, & Hallquist, 2008; Raz et al., 2006). Consistent with this conceptual trajectory, suggestions may elicit elevated perceptual effects when combined with hypnotic induction (Derbyshire et al., 2009; McGeown et al., 2012).

Sensation and Perception

Hypnotic and posthypnotic suggestion can alter perception in dramatic fashion (Kihlstrom, 2008). From induced hallucinations to the suppression of pain sensations, evidence shows that suggestion directed at modulating perception influences sensory processing and the conscious representation of sensory events. These suggestions typically engage frontal and sensory areas of the human brain (see Figure 3). Critically, studies primarily highlight the capacity for suggestions to selectively target a particular perceptual neural system; for example, suggestions to change visual perception correlate with modulation of visual processing (Kosslyn et al., 2000; McGeown et al., 2012; Raz, 2005), while suggestion to alter pain perception afflict somatosensory areas and the ACC, two central nodes involved in pain perception (Abrahamsen et al., 2010; Derbyshire et al., 2004, 2009; Hofbauer et al., 2001; Raij et al., 2005, 2009; Rainville et al., 1997, 1999; Wik et al., 1999). Moreover, suggestion possesses the selective capacity to precisely target components of subjective appraisal related to pain perception (Hofbauer et al., 2001; Rainville et al., 1997). Evidence also indicates that posthypnotic suggestion can target higher processes concerned with perception, including valence judgments (Ludwig et al., 2013).

Carefully crafted perceptual suggestions can bring about powerful effects (for review, see Lifshitz et al., 2013a). For example, suggestions to modify reading derail the ballistic response in the Stroop effect, leading to marked improvements in task performances (Raz et al., 2002). Matching neural patterns accompany these behavioral

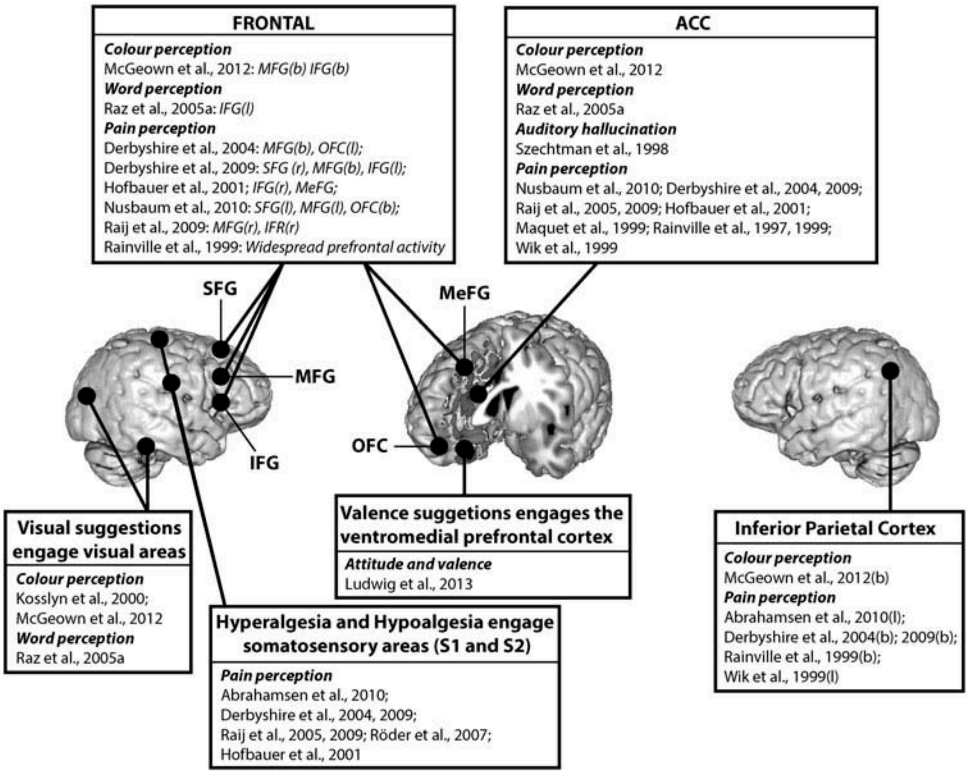

FIGURE 3 Brain regions related to sensation and perceptual suggestions (laterality: “r” for right, “l” for left, and “b” for bilateral).

results, wherein a specific posthypnotic suggestion to obviate reading induces modulations of the visual areas and reduces ACC activity (Raz et al., 2005a). This neural pattern proposes that suggestion likely mediates early sensory processing, subsequently altering orthographic and semantic processing, which results in reduced cognitive conflict between the reading and color-naming responses in the Stroop task. The contrast between the completion of the Stroop task with and without posthypnotic suggestions affords an examination of how suggestion may lead HHSs to adopt a potential heuristic stratagem.

Hypnotic hallucinations are astonishing perceptual phenomena, which have been thoroughly documented in the laboratory (Bryant & Mallard, 2003; Kallio & Koivisto, 2013; Koivisto, Kirjanen, Revonsuo, & Kallio, 2013; Kosslyn et al., 2000; Mazzoni et al., 2009; McGeown et al., 2012; Spiegel, 2003; Szechtman et al., 1998; Woody & Szechtman, 2000). Most imaging studies of hypnotic hallucinations report corresponding sensory activation; activation of perceptual representations is likely at the core (Derbyshire et al., 2004; Kosslyn et al., 2000; McGeown et al., 2012; Raij et al., 2005). Consistent with other forms of hallucinations (Allen, Larøi, McGuire, & Aleman, 2008), one hypothesis postulates that these particular experiences stem from distorted monitoring of reality, leading to misapprehension of mental representation and perceptual experience (Bryant & Mallard, 2003, 2005). In support of this view, hypnotic alterations of the ACC have been reliably reported during various forms of hypnotic hallucinations (Derbyshire et al., 2004; McGeown et al., 2012; Raij et al., 2005; Szechtman et al., 1998). Other findings propose that the involvement of the right DLPFC correlates with the intensity of the hallucination (Raij et al., 2009). These neuroimaging reports are reminiscent of dissociation theories wherein the breakdown in communication between control and monitoring processes may explain lapses in the proper evaluation and interpretation of perceptual representations.

Memory

Ongoing investigations of PHA, pseudomemory inception, and induced identity disorders attempt to unravel the underlying cognitive mechanisms (Barnier, 2002; Barnier, McConkey, & Wright, 2004). Most research efforts, however, shy away from examining the corresponding neural mechanisms.

Posthypnotic suggestions can cause transient amnesia upon termination of hypnosis. This functional deficit may occur across a wide range of content. Importantly, the reversal of such memory lapses via a prearranged cue implies that PHA mainly reflects a dysfunction of retrieval processes (Kihlstrom, 1997). Hence, PHA chiefly hampers accessibility rather than availability of stored content. Neuroimaging findings from PHA studies support this interpretation (see Figure 4; Mendelsohn et al., 2008). These results show that PHA correlates with decreased activity in the left temporal pole and extrastriate areas—both typically implicated in the recollection of stored information (Dolan, Lane, Chua, & Fletcher, 2000; Johnson & Rugg, 2007; Tranel, 2009). PHA, therefore, seems to impede the reactivation and reconstruction of encoded material during retrieval. Increased activity in regions associated with retrieval procedures following the reversal of PHA further supports this explanation. Moreover, PHA links to increased activity in the rostral area of the prefrontal cortex (PFC; see Figure 4; Mendelsohn et al., 2008), a region notably involved in the top-down regulation of retrieval strategies (Burgess, Gilbert, & Dumontheil, 2007; Gilbert et al., 2006; Lepage, Ghaffar, Nyberg, & Tulving, 2000). Accordingly, in lieu of normal retrieval procedures, PHA-related PFC activation may operationalize the top-down influence that actively suppresses retrieval of stored content, keeping this material out of reach for conscious report.

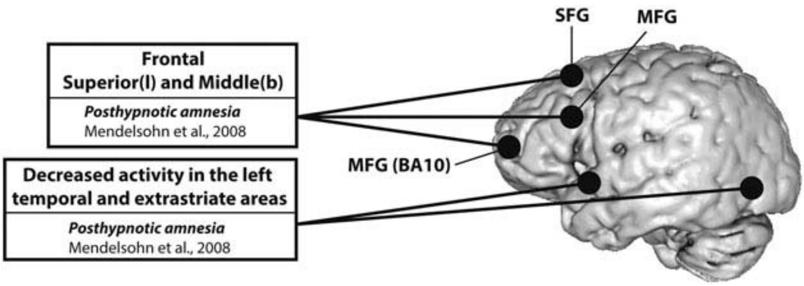

FIGURE 4 Brain regions related to memory suggestions.

Ideomotor Action

Ideomotor suggestions interfere with the planning, execution, and monitoring of actions, thereby altering the production of action and corresponding sense of agency (i.e., the feeling of causing one's action; Polito, Barnier, & Woody, 2013). Due to their ability to accurately target systems involved in the preparation and production of actions, these suggestions serve as a reliable experimental instrument to explore the mechanisms of volition and volitional disorders (Bell, Oakley, Halligan, & Deeley, 2011). Ideomotor suggestions predominantly engage the frontal, motor, parietal, and cerebellar regions (see Figure 5).

Hypnotic paralysis renders HHSs incapable of producing specified actions (Halligan et al., 2000), whereas hypnotic alteration of the sense of agency distorts the subjective feeling of control over actions (Blakemore et al., 2003). Both phenomena modulate characteristic brain areas involved in the production and monitoring of action—i.e., motor cortex, cerebellum, and parietal regions (Blakemore et al., 2003; Cojan et al., 2009; Deeley et al., 2013a, 2014; Ward et al., 2003). Moreover, while hypnotic paralysis corresponds to reduced motor activity (Deeley et al., 2013a), preparatory motor activity remains largely intact (Cojan et al., 2009). These primary results critically intimate that hypnotic paralysis hardly impairs motor intentions, but rather interferes with later scripts of action production.

Suggestions to induce hypnotic paralysis usually engage the frontal areas (see Figure 5). As such, neuroimaging studies report key differences in frontal activity between hypnotic paralysis and controlled conditions, including feigned paralysis and voluntary motor inhibition (Ward et al., 2003). The IFG—typically active during voluntary motor inhibition (Hampshire, Chamberlain, Monti, Duncan, & Owen, 2010; Swick, Ashley, & Turken, 2008)—remains active throughout hypnosis, including throughout conditions that require participants to use their non-paralyzed hand (Cojan et al., 2009). Similarly, hypnotic paralysis engages the MFG (Burgmer et al., 2013; Cojan et al., 2009).

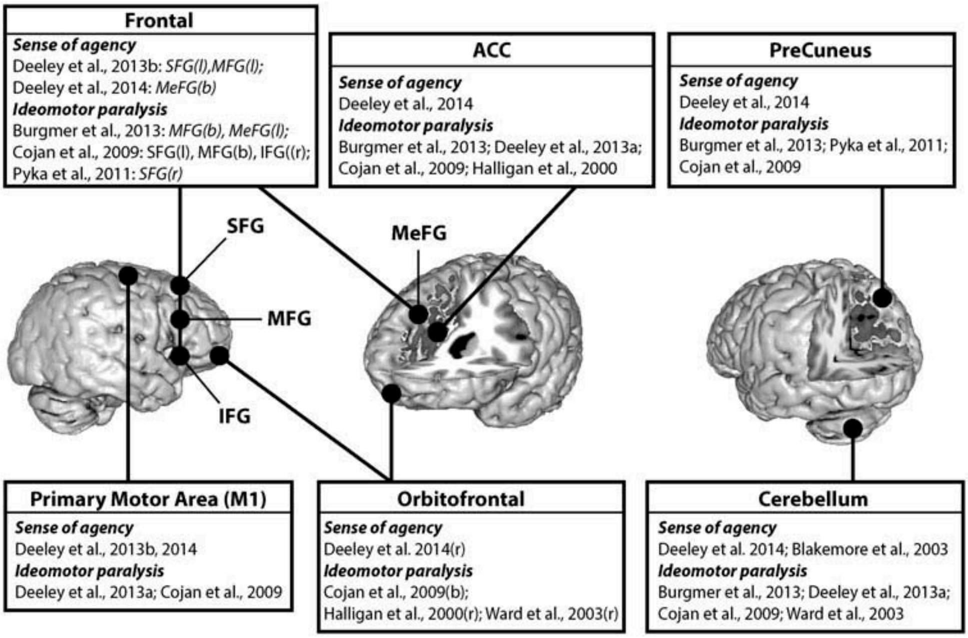

FIGURE 5 Brain regions related to ideomotor suggestions.

Contrary to earlier assumptions (Halligan et al., 2000), recent findings undermine the idea that the orbitofrontal cortex (OFC) directly mediates motor inhibition during hypnotic paralysis (Burgmer et al., 2013; Cojan et al., 2009). Consistent with other neuroimaging assays of hypnosis (Abrahamsen et al., 2010; Deeley et al., 2014; Derbyshire et al., 2004; Halligan et al., 2000; Nusbaum et al., 2010; Raij et al., 2009; Ward et al., 2003; Wik et al., 1999), OFC activity during hypnotic paralysis appears to reflect an overall effect of hypnotic, rather than sheer response, inhibition. Consistent with this view, the OFC relates to expectation (Schoenbaum & Roesch, 2005), a top-down process of central importance in hypnotic phenomena (Kirsch, 1997; Lifshitz, Howells, & Raz, 2012; Raz, 2011b).

Neuroimaging studies of ideomotor suggestions also underline activation of the precuneus (Burgmer et al., 2013; Cojan et al., 2009; Deeley et al., 2014; Pyka et al., 2011), a brain region notably involved in the processing of spatial information (Cavanna & Trimble, 2006; Northoff & Bermpohl, 2004), and self-referential procedures (Cabanis et al., 2013). Accordingly, ideomotor suggestions seemingly act through the modulations of spatial representation of actions, representations of the self, or both. Other findings highlight the role of other parietal regions in the hypnotic modulation of the sense of agency (e.g., parietal operculum, Blakemore et al., 2003; superior parietal lobule, Deeley et al., 2014). These results supplement experimental reports that link the inferior parietal region to action monitoring and the subjective experience of agency (Chambon, Wenke, Fleming, Prinz, & Haggard, 2013). In addition, ideomotor suggestion alters connectivity between several brain regions, including the prefrontal, supplementary, and primary motor area, and the parietal region, which leads to loss of perceived control during arm movement and decreased awareness of involuntary movements (Deeley et al., 2013b, 2014). Collectively, these results bolster the notion that motor preparation and the planning of action in the frontal and parietal sites relate to fundamental dimensions of the phenomenology of action and agency. They also highlight how ideomotor suggestions can modify the coupling between various brain regions, altering production of action and sense of agency.

Finally, ideomotor suggestions also encompass activation of the ACC (see Figure 5). During hypnotic paralysis, the ACC activity may potentially arise from the incongruence between the desired and actual outcome (Burgmer et al., 2013; Deeley et al., 2013a). According to this view, ACC activity indexes the online detection of a conflict between the explicit intent and the observed result. Attempted movements during paralysis correspond to altered connectivity between the ACC and the motor cortex (Burgmer et al., 2013), as well as between the ACC and supplementary motor area (Deeley et al., 2013a). However, the prevalence of ACC activation in the neurocognitive literature of hypnosis suggests that this brain region likely indexes a main effect of hypnosis rather than task-specific effects (Casale et al., 2012). Supporting this latter interpretation, a neuroimaging study of hypnotic paralysis reports ACC activity during each hypnotic experimental condition, including situations that did not require attempts to move the paralyzed limb (Cojan et al., 2009). This result strongly supports the idea that ACC activity reflects a global effect related to hypnotic phenomena.

Conclusions

The wide spectrum of results from neuroimaging studies of hypnosis emphasizes the need to follow tightly controlled experimental designs to better constrain the neural correlates subserving specific hypnotic phenomena (Mazzoni et al., 2013). Moreover, the fact that few studies compare HHSs and LHSs diminishes the general validity of results. Focusing on HHSs alone impedes generalizability and overlooks inter-individual variability in hypnotic responses (Heap et al., 2004; Laurence et al., 2008). Centrally, the distinction between induction and suggestion remains imprecise (Kihlstrom, 2008). Moreover, because most studies investigate hypnotic effects within a task, it remains difficult to experimentally isolate hypnotic-specific from task-specific effects. Beyond employing experimental designs that account for individual differences, evidence from various methodological approaches must be combined to inform and triangulate findings. For example, a recent study reports that temporary disruption of the left DLPFC with repetitive transcranial magnetic stimulation leads to increased sensibility to hypnotic suggestion (Dienes & Hutton, 2013). In this regard, neuroimaging permits researchers to further appreciate the central role of specific brain regions in hypnotic response. Likewise, the combination of first-person approaches with cutting-edge brain-imaging techniques provides a reliable paradigm to explore the neuroscience of subjective experiences (Lutz & Thompson, 2003). The neurophenomenology of hypnosis therefore affords researchers with unique insights concerning the phenomenological properties of hypnosis and their underlying neural correlates (Lifshitz, Cusumano, & Raz, 2013b).

The difference between hypnotic induction with and without task-specific suggestions underscores the importance of suggestions in causing hypnotic phenomena (Egner & Raz, 2007). Suggestion can induce potent effects; however, while the absence of task-specific suggestions relates to poor performance, posthypnotic suggestions may provide HHSs with reliable cognitive strategies that lead to substantial increases in performance. Neuroimaging findings substantiate this contrast. Hypnotic induction in the absence of task-specific suggestions corresponds to fronto-thalamic modulations—presumably reflecting engagement of attention—accompanied by deeper relaxation (Rainville et al., 2002). Neural responses to suggestion showcase the potential of hypnosis to selectively target brain processes (Oakley & Halligan, 2009, 2013). However, because findings cut across various types of suggestion, each engaging a specific system, commonalities between categories of suggestions remain difficult to pinpoint. The prospect of a reliable neurobiological model of hypnosis, therefore, requires a finer appreciation of the science of suggestion (Halligan & Oakley, 2014; Michael et al., 2012). Overall, the interactions between inter-individual variability, hypnotic responses, and hypnotic induction paint a complex picture (Mazzoni et al., 2013). Most modern views attempt to account for this complexity in terms of alterations of attention, expectation, cognitive control, and monitoring (Kihlstrom, 2014; Kirsch, 1997; Maldonado & Spiegel, 2008; Raz, 2004; Woody & Sadler, 2008).

Neuroimaging studies of hypnosis reveal a primary role of top-down modulations indexed by PFC and ACC activity. Dissociation theories argue that most hypnotic phenomena stem from a decoupling of control and monitoring processes (Woody & Farvolden, 1998; Woody & Szechtman, 2000). According to this model, PFC activity reflects the selection and implementation of hypnotic responses, while modulations of the ACC index changes in monitoring. This decoupling between control and monitoring procedures seems to enable suggestions to bypass evaluative procedures and directly act upon control processes. This dissociation subsequently leads to misrepresentations of hypnotic responses in consciousness (Kihlstrom, 2008). Specifically, without proper monitoring feedback, the implementation of the hypnotic response is less attributable to the self and remains beyond subjective feelings of control. In sum, hypnosis yields substantial changes in attention, control, and monitoring processing. It is likely that patterns of neural activity in the frontal areas operationalize these changes.

Here we argue that the hypnotic experience alters connectivity between numerous brain regions. However, neuroscientists are gradually mapping out the spatial location and time-course of neural events pertaining to hypnotic phenomena (Halligan & Oakley, 2013; Kihlstrom, 2013). Overall, neuroimaging studies not only deliver a better framework to understand hypnotic phenomena, but they supplement the important phenomenological accounts and subjective impressions of participants with objective measures of direct and indirect physiological indexes (Cusumano & Raz, 2014; Lifshitz et al., 2013b; Raz & Lifshitz, 2015). This juxtaposition paves the road to a more scientific understanding of hypnosis.

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