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Research Report

An interhemispheric frontoparietal network supports hypnotic states

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ABSTRACT

Understanding the neural substrate of altered conscious states is an important cultural, scientific, and clinical endeavour. Although hypnosis causes strong shifts in conscious perception and cognition, it remains largely unclear how hypnosis affects information processing in cortical networks. Here we manipulated the depth of hypnotic states to study information processing between cortical regions involved in attention and awareness. We used high-density Electroencephalography (EEG) to record resting-state cortical activity from 30 hypnosis experts during two hypnotic states with different depth. Each participant entered a light and a deep hypnotic state as well as two well-matched control states. Bridging top-down and lateralisation models of hypnosis, we found that interhemispheric frontoparietal connectivity distinguished hypnosis and control conditions, while no difference was found between the two hypnotic states. Using a graph-theoretic measure, we revealed that the amount of information passing through individual nodes (measured via betweenness centrality) is reduced during hypnosis relative to control states. Finally, we found that theta power was enhanced during hypnosis. Our result contributes to the current discussion around a role for theta power in bringing about hypnotic states, as well as other altered conscious states. Overall, our findings support the notion that altered top-down control in frontoparietal regions facilitates hypnosis by integrating information between cortical hemispheres.

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1. Introduction

A major challenge in neuroscience is to uncover the neural signatures of conscious states (Koch, Massimini, Boly, & Tononi, 2016). An important step to address this challenge is to understand the neural underpinnings of altered conscious states by studying phenomena such as dreaming (Mutz & Javadi, 2017), meditation (Tang, Hölzel, & Posner, 2015), shamanic (Flor-Henry, Shapiro, & Sombrun, 2017), psychedelic (Preller et al., 2019), or hypnotic states (Gruzelier, 2005). A dominant school of thought frames hypnosis as a behavioural and cognitive technique which uses attention and suggestion to induce highly focused perceptual, emotional, and cognitive states without the need for changes in sensory input (Jensen et al., 2017; Oakley & Halligan, 2013). We define the hypnotic state as the psychological experiences and neural differences arising due to hypnotic procedures. In the hypnotic state, individuals might experience an altered sense of their own body and agency of their movements, vivid mental imagery, distorted time perception, or strong feelings of joy (Landry, Lifshitz, & Raz, 2017). Beyond subjective experiences, hypnosis can interfere with processes governing cognitive control such as lexical processing in a Stroop task (Raz, Shapiro, Fan, & Posner, 2002), hypnotic analgesia (Moss & Willmarth, 2019; Thompson et al., 2019), or hypnotically induced memories (Kihlstrom, 1997; Laurence & Perry, 1983). Although the view that hypnosis elicits an altered state of consciousness has been contested (Graham, 1997; Jay Lynn, Kirsch, & Hallquist, 2008; Kirsch et al., 2008; Sarbin & Andersen, 1967; Theodore, 1972; Barber, 1958), there is mounting consensus in cognitive neuroscience that hypnotic states are linked to distinct neural activation patterns influenced by attention and expectation (Jensen et al., 2017; Terhune, Cleeremans, Raz, & Lynn, 2017). Based on the observation that hypnosis induces profound perceptual changes in susceptible individuals, there has been increasing interest to apply hypnotic suggestion in clinical settings such as analgesia (Moss & Willmarth, 2019). Despite much progress, considerable controversy surrounds the neural underpinnings of hypnotic states (Landry et al., 2017).

There is broad agreement that the frontal cortex supports hypnotic states (Landry et al., 2017), although its exact role remains unclear. Evidence supports the idea that the frontal default mode network is deactivated during hypnotic states (McGeown, Mazzoni, Venneri, & Kirsch, 2009) whereas brain networks supporting saliency and cognitive control are more engaged (Jiang, White, Greicius, Waelde, & Spiegel, 2017). Converging studies show that hypnotic states are associated with increased theta power, which is thought to be a marker of cognitive control (Nigbur, Ivanova, & Stürmer, 2011), in highly hypnotisable participants (Graffin, Ray, & Lundy, 1995; Kirenskaya, Novototsky-Vlasov, & Zvonikov, 2011; Sabourin, Cutcomb, Crawford, & Pribram, 1990; Williams & Gruzelier, 2001). A closer examination of the literature reveals that studies elucidating power spectrum differences during hypnotic states produce heterogeneous results. Some studies did not replicate a boost in theta power during hypnotic states (de Pascalis, 1999; Hiltunen et al., 2021; Jensen, Adachi, Tomé-Pires, et al., 2015). Across multiple studies, hypnotic states were linked to increases in alpha-band power in posterior cortical regions (Williams & Gruzelier, 2001), frontal beta-band activity (Fingelkurts, Fingelkurts, Kallio, & Revonsuo, 2007), or no power spectral differences at all (Blair et al., 2011; Jamieson & Burgess, 2014).

Similar to other altered conscious states characterised by the attentional absorption into an experience (Timmermann et al., 2023), hypnotic states are thought to alter information passing between cortical regions linked to attention and awareness. Several theories consider hypnotic states to rely on frontoparietal top-down influences on sensory processes (Gruzelier, 2006; Oakley & Halligan, 2013; Raz, 2011; Terhune et al., 2017). Especially in highly hypnotisable individuals, hypnotic states enhance top-down information transmission from frontal executive control networks to saliency-related areas such as the anterior cingulate cortex and the insula but decrease frontal connectivity to the default mode network (Hoeft, Gabrieli, Whitfield-Gabrieli, Haas, & Bammer, 2012; Huber, Lui, Duzzi, Pagnoni, & Porro, 2014; Jiang et al., 2017). Consistent with the notion that hypnotic states rely on inhibitory mechanisms in the frontal cortex, hypnotic states were found to increase theta-band connectivity in parietal brain regions but also decrease beta-band connections between frontocentral and occipital areas (Jamieson & Burgess, 2014). Others found evidence for increased frontoparietal connectivity in the delta-band while connectivity in a more widespread network involving frontal, central and parietal hubs in the alpha and beta frequency range decreased (Panda et al., 2023).

Beyond top-down mechanisms, cortical lateralisation has been thought to play a role in facilitating hypnotic states, although there is disagreement over whether left- or right–hemispheric processes are more strongly linked to hypnotic states (De Pascalis et al., 2020; Kihlstrom, 2013; Lanfranco, Rivera-Rei, Huepe, Ibáñez, & Canales-Johnson, 2021; Paul, 1969). Converging evidence from electroencephalography (EEG) and functional magnetic resonance imaging (fMRI) studies supports earlier views of a right-lateralised network involved in hypnotic states (Gruzelier, 1998). Early work identified a bias towards right-hemispheric processing in electrodermal responses sampled during behavioural tasks in the hypnotic state (Gruzelier, Brow, Perry, Rhonder, & Thomas, 1984). More recently, visual hypnotic hallucinations were found to recruit a right-hemispheric network (Lanfranco et al., 2021). Other behavioural and electrophysiological studies point towards a link between hypnotic states and left-hemispheric dominance in information processing (De Pascalis et al., 2020). For example, hypnotic states were linked to a left-lateralised increase in beta power in highly hypnotisable people (Sabourin et al., 1990). Others found that left–hemispheric processes were associated with hypnotic depth (Cardeña et al., 2012). Patients with complete brain damage in either the left or right hemisphere show no difference in hypnotisability, suggesting that neither hemisphere is essential to bring about a hypnotic state (Kihlstrom, Glisky, McGovern, Rapcsak, & Mennemeier, 2013). Overall, the findings illustrated above show that lateralisation and interhemispheric processes might play a role in hypnotic states but are not critical to enter those states.

A challenge to hypnosis research is that the literature on cortical markers of hypnotic states is riddled with inconsistent and conflicting findings. In a recent meta-analysis of neural changes linked to hypnotic states, only 18 papers met quality requirements for inclusion (Wolf, Anna Faerber, Rummel, Halsband, & Campus, 2022). In part, heterogeneity in research findings might result from methodological challenges such as small sample sizes (Lipari et al., 2012) or lack of matched control conditions (Rainville, Hofbauer, Catherine Bushnell, Duncan, & Price, 2002). Other reasons for variability include heterogeneous definitions of hypnosis, induction techniques and cognitive strategies employed by participants to enter hypnotic states (Landry et al., 2017). To account for those criticisms, our group aimed to investigate the neural correlates of the hypnotic state itself in a multi-study project using a range of testing modalities (fMRI, MR spectroscopy and EEG) (de Matos, Staempfli, Seifritz, Preller, & Bruegger, 2023).

Here we address the interplay of top-down control and interhemispheric information transmission in hypnotic states with different depth. Considerable controversy surrounds the notion of hypnotic depth (Jonathan McGeown, Mazzoni, Vannucci, & Venneri, 2015; Pekala, Kumar, Maurer, Elliott-Carter, & Moon, 2006; Terhune & Cardeña, 2010). Much work addressing hypnotic depth centres on interindividual differences in hypnotisability during an experiment (Jonathan McGeown et al., 2015; Zech, Seemann, & Hansen, 2023). Our study takes a different approach to assessing hypnotic depth. In a cohort of 30 hypnosis experts, we compared resting-state cortical activity sampled using high-density EEG in two hypnotic states with different levels of depth, as well as matched control states. Based on de Matos et al. (de Matos et al., 2023), we operationalise hypnotic depth as the extent to which an individual enters a hypnotic state. To understand how hypnotic depth influences neural and psychological markers of hypnosis, we induced two distinct hypnotic states with different depth using a standardised induction text developed in de Matos et al., 2023.

Our experimental design aims to overcome methodological issues by employing standardized induction and control conditions matching the hypnosis induction in semantic content but without inducing the hypnotic effect. Our hypotheses were tested in a group of hypnosis experts which received standardized training to achieve hypnotic states. We also adopted a hypnosis protocol in which no specific suggestion other than relaxation is given after the induction of hypnosis. Considering that findings linking hypnotic states to top-down neural activity are frequently inconsistent (Terhune et al., 2017), an open question is whether and how hypnosis impacts frontoparietal mechanisms supporting top-down regulation. To understand the putative neural underpinnings of hypnotic states, we set out to determine whether inter- and intra-hemispheric information flow between the frontal cortex and central as well as parietal hubs differentiates hypnotic states from control states, and levels of hypnotic depth. We also tested whether spectral power, in particular a theta power increase (Williams & Gruzelier, 2001), might differentiate hypnotic from control states as well as states with different hypnotic depth. Based on previous findings linking altered states of consciousness in meditation (Lardone et al., 2022) or epilepsy (Varotto et al., 2021) to graph-theoretical measures in EEG, we investigated whether the intrinsic organisation of cortical networks (measured using betweenness centrality) differentiates both hypnotic states, as well as hypnotic and control states. A second goal of our study was to link putative differences in connectivity in a fronto-parietal network to changes in subjective experience during hypnosis. To this aim, we added a short questionnaire about the phenomenal experience immediately after the experience, as well as a more detailed questionnaire about the different states after the full experience. To better understand how attention-related networks might be influenced by hypnosis, we also tested for links between trait measures of attentional absorption and cortical information flow.

2. Methods

2.1. Participants

We recruited 40 participants (M = 50.62, SD = 7.83, 75% female) into the EEG part of the hypnosis study taking place at the University of Zurich. Participants were not reimbursed for their participation in the study. The study received approval from the Zurich cantonal ethics committee (2018-00550). Data from 10 participants could not be further analysed due to low data quality resulting from technical difficulties (demographic information specific to the subset was not available). Despite that, our sample size is comparable to other studies in the literature (Landry et al., 2017). We approached participants through the OMNI member portal which only includes individuals trained in administering and receiving hypnosis by the OMNI Hypnosis Training Centre in Switzerland (https://omnihypnosis.com/). Participants included in the study had been practicing self-hypnosis every week for a minimum of two months when the study was performed. Only individuals aged 18–65 with proficiency in German were asked to participate in the study. We excluded individuals with neurological, psychiatric or any other medicated chronic conditions as well as a history of brain injury, alcohol, or drug abuse. Due to Covid-19 regulations, we also did not approach individuals with cancer, cardiovascular disease, chronic respiratory disease, diseases, and therapies that weaken the immune system, diabetes, high blood pressure, obesity grade III, and pregnant people. Participants gave their informed consent and completed an assessment of the Federal Office for Public Health in Switzerland as a part of Covid-19 measures one day prior to the experiment. Everyone participating in the experiment was asked to wear a mask during the task. Participants' mean score on the Tellegen Absorption Scale was 114.03 (SD = 19.85), suggesting that participants share high attentional absorption as a trait. Exclusion and inclusion criteria were determined before the start of the study.

2.2. Study procedure

The experiment took place in a faraday cage at the Department of Psychology at the University of Zurich. Participants were asked to sit on a chair leaned back and with their eyes closed. To record EEG/ECG data, we used a water-based EGI

Geodesic Sensor Net (GSN) HydroCel system with 128 electrodes, a Net Amps amplifier and Net Station (Version 4.4.2). To induce hypnotic states, a group of three hypnotherapists with a hypnosis training certification awarded by the OMNI Hypnosis Training Centre. One hypnotherapist delivered instructions to induce hypnotic and control states via speakers. Due to COVID-19 regulations, the hypnotherapist was not allowed to stay in the Faraday cage. Before the EEG recording, participants filled out the Tellegen Absorption Scale (TAS) (Jamieson, 2005; Tellegen & Atkinson, 1981). Afterwards, a baseline EEG recording of 3 min was obtained and participants were assigned to either start the experiment with the control condition followed by the hypnotic condition, or vice versa, in counterbalanced order. Texts to induce hypnotic and control states were administered in German and matched in word frequency and phrasing. Following the induction of either hypnotic or control state, EEG was recorded for 8 min. After the final EEG recording, the participant was dehypnotized. In the hypnosis condition, the hypnotherapist initially induced Hypnotic State 1 (HS1). Following an interval during which EEG was recorded, the hypnotherapist performed hypnotic deepening to evoke Hypnotic State 2 (HS2). For the control condition, an equivalent procedure involving a control induction followed by Control State 1 (CS1) and control deepening followed by Control State 2 (CS2). EEG was measured during hypnotic and control states. After both the hypnosis and the control sequence, the participant was prompted to fill out a short conscious experience questionnaire (CEQ) based on a modification of the Phenomenology of Consciousness Inventory (Pekala & Levine, 1982). This questionnaire was used to measure changes in participants' subjective experience during the hypnotic or control state. In 22 items using a continuous scale from 0 to 100 (0 = "not more than usual", 100 = "a lot more than usual"), this questionnaire records different aspects of attention, awareness, emotion, time, and body perception. This questionnaire was extended with a rating of the perceptibility of one's bodily boundaries (on a discrete scale from 0 to 7; 0 = my bodily boundaries are a lot less perceptible than usual, and 7 = my bodily boundaries are a lot more perceptible than usual). Finally, participants were asked to fill out an online version of the Altered States of Consciousness (ASC-11D) questionnaire, which quantifies conscious states across eleven dimensions (Studerus, Gamma, & Vollenweider, 2010) to describe their experience during the two hypnotic states at home within 48 h of completion of the experiment. During the debriefing, the experimenter verified with the participant that the hypnotic state they entered during the experiment resembled their past experiences with hypnosis.

2.3. Data preprocessing

EEG preprocessing was performed using the EEGLAB toolbox in Matlab r2021b. Initially, we resampled the EEG data from 512 Hz to 128 Hz and applied a notch filter at 50 Hz to remove line noise. We excluded data from electrodes at the cheek and forehead which are contaminated by muscle and sweat artefacts. Finally, we applied a butterfly bandpass filter between .5 and 40 Hz and divided up the continuous EEG recording in 1s segments. We referenced data to the common average. Using a semi-automated procedure, we removed segments with a variance threshold of 250 mV and channels exceeding a threshold of 500 mV automatically, as well as other noisy channels and segments by visual inspection. To remove noise arising from sweat and motor activity (such as eye movements), we performed independent component analysis. Finally, we interpolated missing channels using the spherical spline algorithm and manually removed any remaining trials still containing artefacts. We rejected ~6% of channels and ~6% of trials. For each of the four conditions, we removed the channel baseline means obtained from the EEG baseline recording.

2.4. EEG analysis

We performed spectral analysis to identify power differences between the hypnosis and control condition, as well as between both hypnotic states relative to control states. For that, we ran a multi-taper Fast-Fourier transform using a Hanning taper in a frequency window of interest between .5 and 40 Hz in steps of .25 on 4 sec data segments without overlap. Having averaged spectral power in each frequency band and per subject (delta .5–4 Hz, theta 4–8 Hz, alpha 8–12 Hz, beta 12–30 Hz, gamma 30–40 Hz), we determined whether normalised spectral power differs between hypnosis and the control condition in the frequency bands of interest. Initially, we assessed whether the condition determines the probability distribution of the power averages sampled during each of the four states. For each frequency band of interest, we initially ran a repeated-measures (i.e., dependent-sample) multivariate ANOVA using a *Monte Carlo* algorithm with 2000 partitions in Fieldtrip ($\alpha = .05$, Bonferroni-corrected). We further analysed significant comparisons with a *Monte Carlo* cluster-based permutation algorithm with 2000 partitions and a two-sided dependent-sample *t*-test ($\alpha = .05$) to identify spatiotemporal clusters in power scalp maps between hypnosis-control condition pairs. To test for interactions, we computed the within-subject contrasts for hypnotic depth and hypnotic state each and compared the resulting difference sets. In a next step, we tested for differences in power envelope correlations between sensors using a connectivity analysis pipeline in Fieldtrip between hypnotic and control states. To implement this analysis, we obtained the Fourier representation of the data using a multi-taper fast-Fourier transform with a DPSS taper and 1 Hz smoothing. Using the Fourier-transformed output data, we calculated power correlations for each electrode pair. We used betweenness centrality, which is a measure of information flow through nodes in a network where nodes on a shortest path are thought to be most central (Brandes, 2001; Freeman, 1978), to test for differences in information flow between hypnotic and control state as well as differences in hypnotic depth. Betweenness centrality is defined as $C_B(v) = \Sigma_{s \neq t \neq v \in V} \frac{\sigma_{st}(v)}{\sigma_{st}}$ where the network is described as a graph $G = (V,E)$ with V being nodes in the graph and E being edges connecting the nodes. σ_{st} defines the number of shortest paths from s to t and $\sigma_{st}(v)$ describes the shortest paths from s to t with $v \not\equiv V$ present in the shortest path. We compared subject-wise averages of betweenness centrality calculated across the entire sensor-space using a non-parametric

aligned-rank-transformed 2(Hypnotic depth: 1/2)×2(Hypnotic state: hypnosis/control) ANOVA. To test for differences in the strength of connections, we selected left and right frontal, central and parietal regions of interest (ROI) (Evans, Maguire, & Sizemore, 2022) and obtained subject-wise connectivity score averages for each ROI pair, condition, frequency band and connectivity metric. Then, we performed a 2(Hypnotic depth: 1/2)×2(Hypnotic state: hypnosis/control) repeated-measures ANOVA in R using the RStatix package v0.7.2 to examine differences between power envelope correlations between conditions. Finally, we determined whether hypnosis-related changes in subjective experience map onto connectivity differences.

Data and code are available here: https://osf.io/2gwnj/. We report how we determined our sample size, all data exclusions, all inclusion/exclusion criteria, whether inclusion/exclusion criteria were established prior to data analysis, all manipulations, and all measures in the study. No part of the study procedures or analysis plans was preregistered prior to the research being conducted.

3. Results

3.1. *Theta power increases during hypnotic states but does not differentiate levels of hypnotic depth*

Theta power enhancement has been observed during altered states of consciousness associated with spiritual experiences (Timmermann et al., 2023), including hypnotic states (Jensen, Adachi, & Hakimian, 2015). In a series of converging analyses, we show that theta power is enhanced during hypnotic relative to control states state but does not distinguish levels of hypnotic depth (Fig. 1). A multivariate cluster-based permutation ANOVA showed power spectrum differences between all conditions in theta ($F(3,27) = 6263.18$, $p = .01$, $\eta^2 p = 1$), but

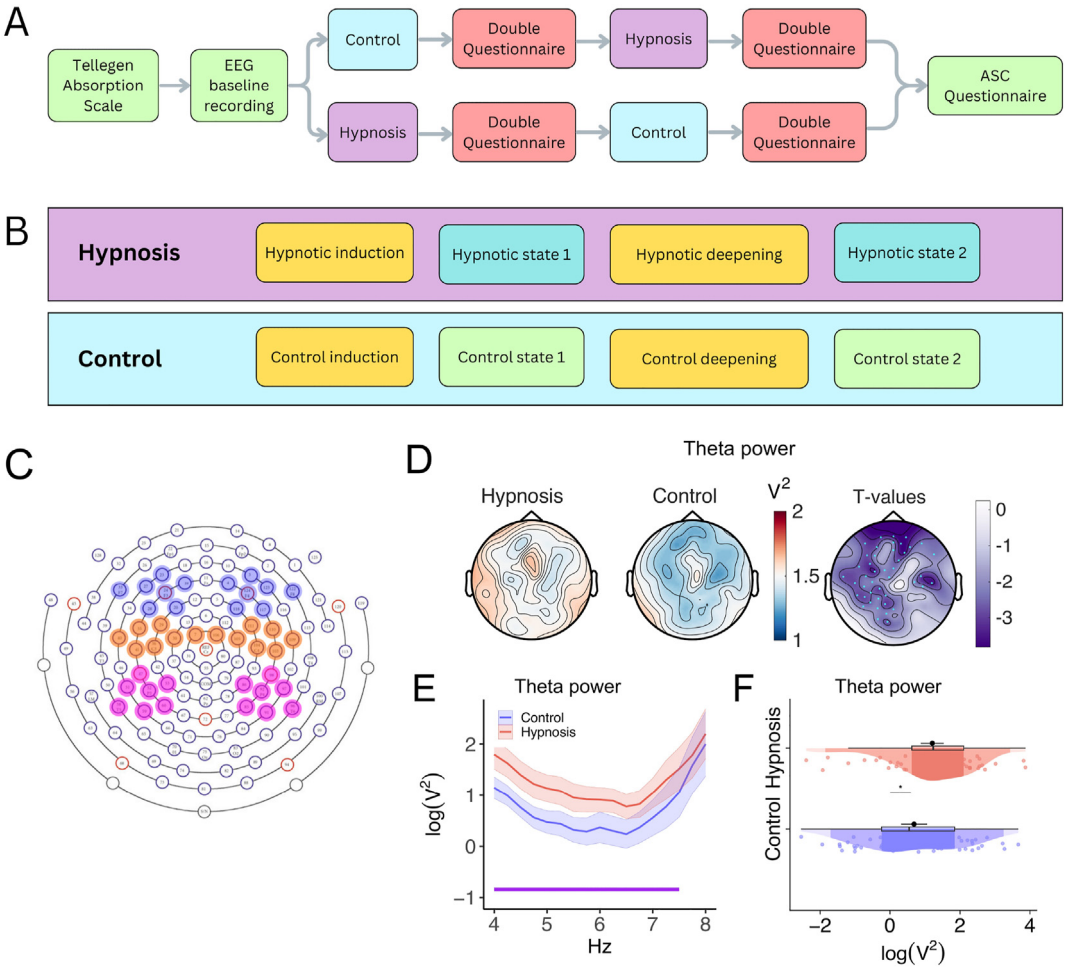

Fig. 1 – (A) Overview of procedure applied in the experiment. (B) Procedure in hypnotic and control sequence. High-density EEG electrode layout with the frontal region of interest in blue, the central region of interest in orange and the parietal region of interest in purple. (C) Regions of interest were divided up in left and right areas along the midline. (D) Theta power scalp map of hypnosis and control. Adjacent T-values map of a cluster-based permutation test comparing hypnosis and control, with adjacent electrodes different from chance highlighted in teal. (E) Average theta-band power-frequency series representing hypnosis and control with the standard error of the mean shaded and significant differences highlighted with a purple bar. (F) Subject-wise theta-band power averages with a density distribution for the hypnosis and control condition, as well as a boxplot and dot whiskers to denote the mean and 95% confidence interval.

not beta (F (3,27) = 2673.90, p = .14, η^2p = 1), gamma (F (3,27) = 3154.42, p = .17, η^2p = 1), delta (F (3,27) = 224.39, p = 1, η^2p = .96) and alpha (F (3,27) = 231.24, p = 1, η^2p = .96). A cluster-based permutation procedure to test for differences between both hypnosis-control difference maps in the theta band revealed no clusters.

To confirm our observation of theta power enhancement during hypnotic relative to control states, we compared power spectra using cluster-based permutation tests of power-frequency series extracted across the entire sensor space (Fig. 1, E). Aligning with our previous findings, this analysis revealed a power enhancement during hypnosis in a cluster between 4 and 7 Hz (t = 42.98, p = .001). To provide additional support for our hypothesis, we performed a 2(Hypnotic depth: 1/2)×2(Hypnotic state: hypnosis/control) repeated-measures ANOVA testing the effect of hypnotic depth and hypnotic state on subject-wise theta power spectra averages (Fig. 1, F). While there was no interaction between the effects of hypnotic state and depth (F (1,29) = .44, p = .52, η^2p = .01), there was a main effect of hypnotic state on theta power scores (t (59) = 3.79, p < .001, d = .49). In line with our expectations, we did not find a main effect for hypnotic depth (F (1,29) = .49, p = .49, η^2p = .02). We also reconfirmed this finding at a subject-level by demonstrating that subject-wise theta power spectra averages are enhanced in hypnosis (M = 1.21, SD = 1.26) relative to control (M = .69, SD = 1.43) in a post-hoc analysis testing for a main effect of hypnotic state (t (59) = 3.79, p < .001, d = .49). In sum, converging analyses support the hypothesis that theta power increases in hypnotic states.

3.2. *Hypnotic depth is associated with experience changes in emotion, attentional absorption and body perception*

We examined how levels of hypnotic depth influence complex emotional, cognitive, and perceptual experiences associated with hypnotic states. To test for those differences, we analysed data from the CEQ which measures changes in subjective experience specific to each of the four states (Fig. 2). For that, we used an aligned-rank-transformed non-parametric 2(Hypnotic depth: 1/2)×2(Hypnotic state: hypnosis/control) repeated measures ANOVA. We also investigated altered

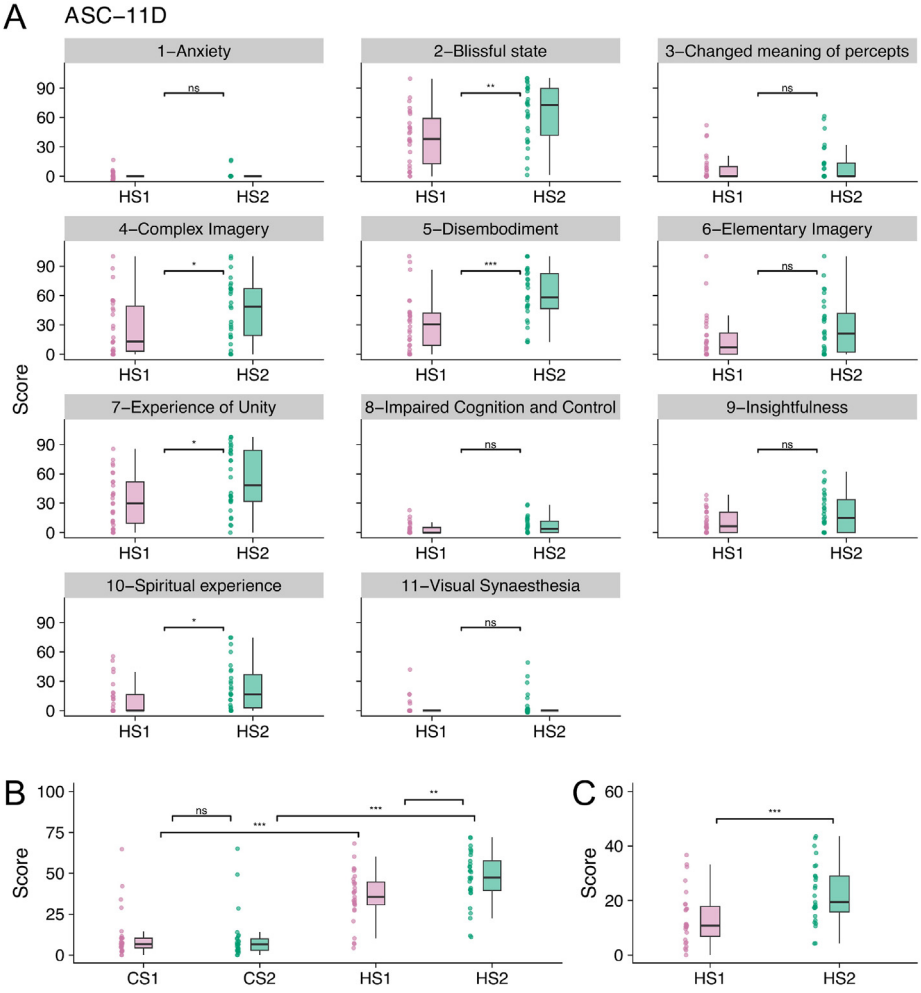

Fig. 2 – (A) Subscales from the ASC-11D questionnaire administered after the experiment, assessing HS1 and HS2. (B) Average scores ASC-11D. (C) Average scores adapted CEQ. Differences between conditions are shown as density distribution plots, with a boxplot to represent the mean and standard deviation and dot whiskers indicate the mean and 95% confidence interval.

conscious experiences linked to hypnotic depth using data from the ASC-11D collected after HS1 and HS2 respectively (Fig. 2, A). To achieve this, we combined subjective ratings from the ASC-11D into 11 subscales in Table 1, Supp. We detail an exhaustive list of results in Tables 2 and 3, Supp. We confirmed high reliability for the TAS with 34 items ($\alpha = .93$), the ASC-11D with 94 items after HS1 ($\alpha = .96$) and HS2 ($\alpha = .95$), and the CEQ with 22 items after HS1 ($\alpha = .88$), HS2 ($\alpha = .85$), HC1 ($\alpha = .94$) and HC2 ($\alpha = .94$).

Subsequently, we discuss how HS2 produced more profound changes in subjective experience than HS1 across different components of hypnotic experience. HS2 was found to be accompanied by deeper spiritual experiences than HS1 (HS2: M = 16.67(IQR = 33.83), HS1: M = 0(IQR = 16.33), W (27) = 491.5, $p = .02$, r = .31, ASC-11D Spiritual experience). After hypnotic deepening, participants felt more unity with their surroundings (HS2: M = 48.4(IQR = 52.1), HS1: M = 29.7(IQR = 42.1), W (28) = 548, $p = .01$, r = .34, ASC-11D Experience of Unity). HS2 led to subjectively experienced deep changes in emotion and cognition. Participants felt more blissful during HS2 than HS1 (HS2: M = 72.67(IQR = 47.83), HS1: M = 38(IQR = 46.17), W (27) = 529.5, $p = .004$, r = .39, ASC-11D Blissful state). Body perception was markedly different during HS2 relative to HS1. Following hypnotic deepening, participants felt a sense of alienation from their own body (HS2: M = 58(IQR = 35.58), HS1: M = 30.5(IQR = 32.92), W (28) = 615.5, $p < .001$, r = .49, ASC-11D Disembodiment). Participants also reported to perceive more complex mental imagery during HS2 than HS1 (HS2: M = 48.67(IQR = 47.83), HS1: M = 13(IQR = 46), W (27) = 494, $p = .03$, r = .31, ASC-11D Complex Imagery).

In our analysis of CEQ average scores, we identified an interaction between hypnotic states and depth (F (1,84)) = 22.03, $p < .001$, .21). We also found a main effect for hypnotic states (F (1,84)) = 252.78, $p < .001$, .75) and depth (F (1,84)) = 15.87, $p < .001$, .16). Post-hoc ART-C procedures revealed a difference between both hypnotic states (t (84) = -15.79, $p = .002$) but not both control conditions (t (84) = 3.17, $p = .88$). There were also differences between HS1 and CS1 (t (84) = -38.03, $p < .001$) as well as HS2 and CS2 respectively (t (84) = -57, $p < .001$).

3.3. *Interhemispheric frontoparietal connectivity supports hypnotic states*

Although there is much controversy surrounding the neural substrate of hypnosis, many models link hypnotic states to altered top-down control (Terhune et al., 2017) and lateralised cortical processing (Coltheart et al., 2018; Naish, 2010; Paul, 1969). Our aim was to determine whether cortical information passing differentiates hypnosis from control conditions, as well as both levels of hypnotic depth. To test for connectivity differences, we ran 2(Hypnotic depth: 1/2)×2(Hypnotic state: hypnosis/control) repeated-measures ANOVAs comparing power correlations between left and right frontal, central and parietal regions of interest for each connection and per frequency band (Fig. 3A and B).

In the beta frequency range, we identified a main effect of hypnotic state for interhemispheric frontocentral (F (1,29) = 10.79, $p = .04$, $\eta^2p = .27$) and centroparietal connectivity scores (F (1,29) = 11.38, $p = .03$, $\eta^2p = .28$). However, there was no main effect of hypnotic depth on connectivity scores in the frontocentral (F (1,29) = .47, $p = 1$, $\eta^2p = .02$) or centroparietal beta-band (F (1,29) = .03, $p = 1$, $\eta^2p = 0$). We did not find an interaction between hypnotic depth and state on connectivity scores in either the right-to-left frontocentral (F (1,29) = 1.65, $p = 1$, $\eta^2p = .05$) or the left centroparietal connection (F (1,29) = .68, $p = 1$, $\eta^2p = .02$) in the beta frequency range. In sum, our results demonstrate beta-band connectivity differences between hypnosis and control conditions. Although our data reveal differences in information messaging between hypnotic and control states, our results do not suggest that hypnotic depth influences connectivity. No interactions of hypnotic depth and state in any frequency band and for any connection survived FDR-correction, suggesting that hypnotic depth did not lead to any differences in cortical messaging.

Finally, we calculated the betweenness centrality of nodes in sensor-space across all electrodes for each frequency band of interest (Fig. 3, C). We identified a difference in betweenness centrality averaged across the scalp separating hypnosis and control conditions in the theta, alpha, and beta band. Using a non-parametric aligned-rank-transformed 2(Hypnotic depth: 1/2)×2(Hypnotic state: hypnosis/control) ANOVA, we identified a main effect of hypnotic state in the theta (F (1,87) = 7.37, $p = .04$, $\eta^2p = .08$), alpha (F (1,87) = 12.37, $p = .003$, $\eta^2p = .12$) and beta bands (F (1,87) = 7.41, $p = .04$, $\eta^2p = .08$). We did not find main effects for hypnotic state in the delta (F (1,87) = .46, $p = 1$, $\eta^2p = .01$) and gamma band (F (1,87) = .93, $p = .56$, $\eta^2p = .01$). There was no main effect of hypnotic depth in either delta (F (1,87) = .07, $p = 1$, $\eta^2p = 0$), theta (F (1,87) = .64, $p = .71$, $\eta^2p = .01$), alpha (F (1,87) = 4.57, $p = .09$, $\eta^2p = .05$), beta (F (1,87) = 0, $p = 1$, $\eta^2p = 0$), or gamma (F (1,87) = 1.11, $p = .56$, $\eta^2p = .01$). Similarly, the ANOVA did not reveal an interaction between hypnotic depth and state in either delta (F (1,87) = 2.17, $p = .72$, $\eta^2p = .02$), theta (F (1,87) = .64, $p = .71$, $\eta^2p = .01$), alpha (F (1,87) = 3.38, $p = .12$, $\eta^2p = .04$), beta (F (1,87) = 1.75, $p = .47$, $\eta^2p = .02$), or gamma (F (1,87) = 3.47, $p = .33$, $\eta^2p = .04$). In line with frontal models of hypnosis, we found that a network involving the propagation of neural information from frontal cortices supports hypnosis. However, our expectation that information passing in a network involving frontal nodes to distinguish hypnotic states with different hypnotic depth was not confirmed.

4. Discussion

In a well-controlled study sampling EEG data from 30 hypnosis experts, we investigated how hypnotic states are associated with altered information messaging in the cortex. Overall, distinct cortical signatures separated hypnotic from control states. Bridging the views that interhemispheric integration as well as cognitive mechanisms in the frontal cortex contribute to hypnotic states, we found that interhemispheric frontoparietal information messaging measured via power envelope correlations is increased during the hypnotic state. Consistent with the idea that frontal attention systems support hypnotic states, frontoparietal connections were linked to trait measures of participants' ability to immerse themselves into an experience. Moreover, hypnosis altered information processing across the entire cortex. In a graph-theoretic analysis, we

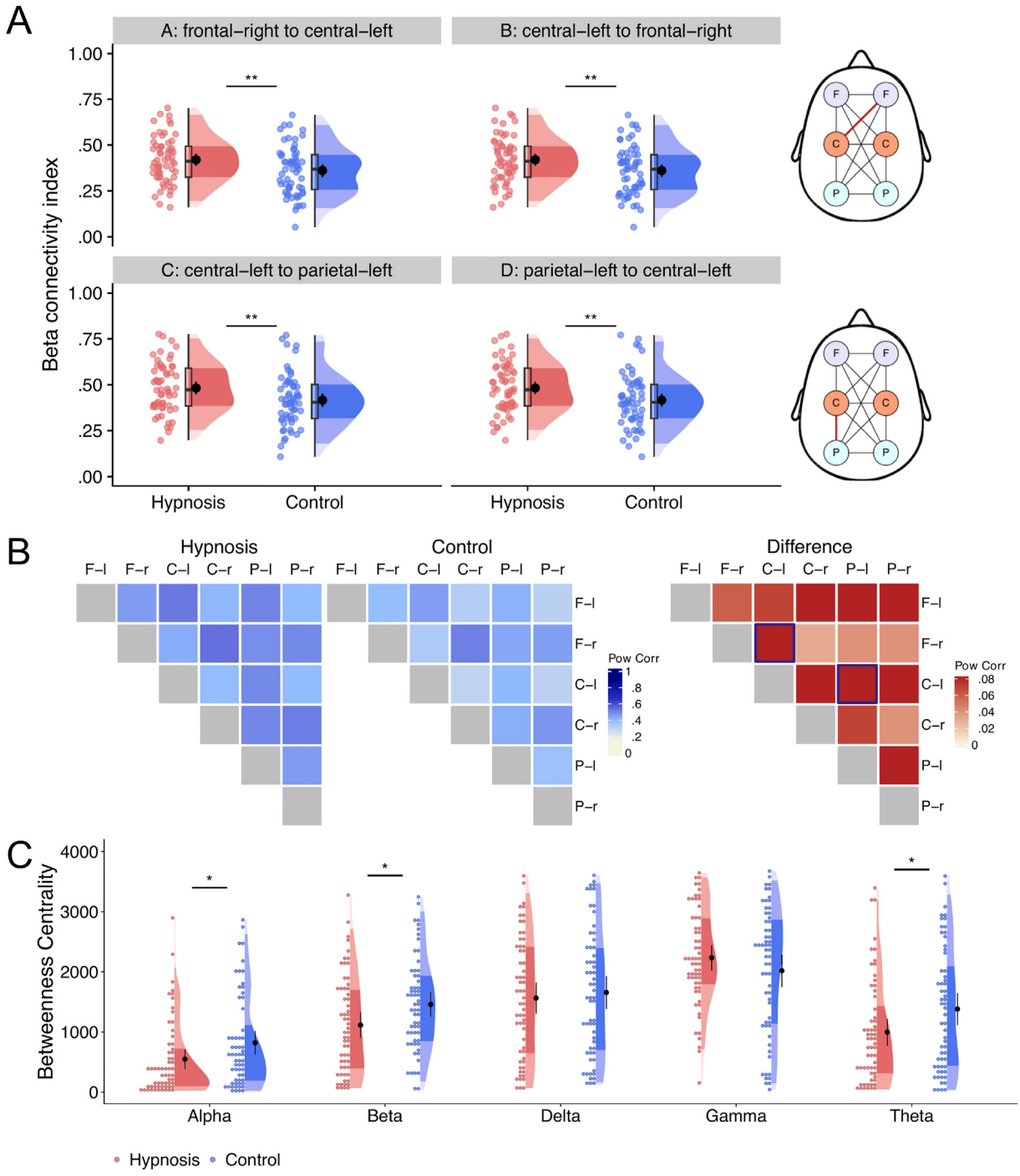

Fig. 3 – (A) Density slabs with a boxplot and a dot indicating the mean connectivity score for hypnosis and control each pooled across both hypnosis and control conditions. Adjacent to the density plots, the network tested for was included in the analysis. Regions of interest are shown as circles and connections which differ from chance are shown in red. (B) Heatmap of power density correlations for hypnosis as well as control on a blue gradient. A power correlation map showing the difference between hypnosis and control is shown in red with significant differences highlighted by a blue rectangle. (C) Betweenness centrality density distributions for hypnosis and control conditions with dot whiskers indicating the mean and 95% confidence interval.

discovered that betweenness centrality calculated in sensor-space was smaller during hypnotic states, reducing the importance individual vertices in sensor-space exert across the entire network. Whereas some previous studies identified enhanced theta power during hypnotic states (Graffin et al., 1995; Kirenskaya et al., 2011; Sabourin et al., 1990; Williams & Gruzelier, 2001), other studies failed to provide evidence for this link (de Pascalis, 1999; Hiltunen et al., 2021; Jensen, Adachi, Tomé-Pires, et al., 2015). Supporting the notion that theta power contributes to the neural correlates of hypnotic

states, we identified a link between hypnotic states and enhanced theta power. Despite large differences in subjective experience separating both hypnotic states, our findings do not substantiate the notion that the neural indices we tested (spectral power, power correlations and power networks) are linked to hypnotic depth.

4.1. *Enhanced theta power indexes hypnosis*

Although hypnotic states have been linked to differences in neural oscillations across different frequency bands (Terhune et al., 2017), theta power enhancement has been suggested to be the most reliable hypnosis-related change in spectral power, possibly due to its role in attentional control (Jensen, Adachi, & Hakimian, 2015; Karakaş, 2020; Posner & Rothbart, 2007). Our finding that spectral power in the theta band is enhanced in hypnotic relative to control states supports earlier suggestions that theta power might be an oscillatory marker of hypnotic states. However, evidence for a role for theta power during hypnotic states is inconsistent. Some groups find that theta is boosted during hypnotic states (Sabourin et al., 1990; Williams & Gruzelier, 2001), while other groups failed to replicate this theta power difference (e.g., in a hypnosis expert using a single-subject design (Hiltunen et al., 2021)). In line with studies reporting theta power as a marker of drowsiness (Canales-Johnson et al., 2020), differences in theta power under hypnosis have been linked to deep relaxation (Williams & Gruzelier, 2001). There is evidence suggesting that increases in theta power reflect more general attention-related processes which might be active during hypnotic states (Fiebelkorn & Kastner, 2019; Kam et al., 2019). Beyond hypnotic states, theta power has been found to be involved in other deep attentional altered conscious states with a spiritual component such as meditation (Baijal & Srinivasan, 2010; Tang, Tang, Rothbart, & Posner, 2019) and mystical psychedelic experiences (Tagliazucchi et al., 2021). Further studies are warranted to determine which experiential aspects of altered conscious states are supported by enhanced theta power.

4.2. *Top-down regulation in an interhemispheric frontoparietal network as amodel for hypnosis*

Our work examined whether hypnosis is linked to altered inter- and intra-hemispheric information flow involving frontal cortices. We identified a network which enables hypnosis-related neural information transmission through an inter-hemispheric connection between left parietal and right frontal regions via a central region. Our finding that the right frontal cortex feeds information to left central regions is compatible with the dominant view that the hypnotic state might be linked to a top-down regulation process recruiting frontal executive networks (Faerman & Spiegel, 2021; Gruzelier, 2006; Raz, 2011; Terhune et al., 2017). Top-down models of hypnosis stipulate that higher-order representations override lower-order sensory inputs in the hypnotic state which manifests in cortical message passing along a frontal-to-posterior cortical hierarchy (Terhune et al., 2017). We extend this view by demonstrating that hypnotic states involve a information propagation in a frontoparietal network across cortical hemispheres.

Our findings dovetail earlier theories of hypnosis assigning cortical lateralisation and inter-hemispheric information transfer a crucial role in bringing about hypnotic states (De Pascalis et al., 2020; Horton, Crawford, Harrington, & Hunter Downs, 2004; Palfi, Parris, McLatchie, Kekecs, & Dienes, 2021). In previous research, hypnosis has been found to alter various aspects of lateralised attentional processing across a series of cognitive tasks. Attentional tasks have been shown to activate the right inferior frontal gyrus more in highly than lowly hypnotisable individuals (Cojan, Piguet, & Vuilleumier, 2015). In hypnotic states, participants were found to recruit the right hemisphere in a dichotic listening task (Crawford, Crawford, & Koperski, 1983; Frumkin, Ripley, & Cox, 1978). Conversely, hypnotic states were associated with left-lateralised information processing in a series of spatial attention tasks in highly hypnotisable people (Diolaiuti, Banfi, & Santarcangelo, 2017; Naish, 2010). Although lateralisation plays a role in hypnotic states, lateralisation theories of hypnosis are not consistent regarding which hemisphere dominates during the hypnotic state (De Pascalis et al., 2020). Refuting the strict notion that exclusively either the left or right hemisphere is critical for hypnotic states, we found that both hemispheres were involved during hypnotic states. Rather than pointing to strict cortical lateralisation, our results reveal that hypnotic states rely on the integration of cortical information across both hemispheres. In support of our own findings showing an interhemispheric information cascade between right frontal and left parietal regions, multiple earlier studies highlight a potential role for interhemispheric information transmission in hypnosis. Increased thickness of the anterior corpus callosum has been reported in highly hypnotisable people (Horton et al., 2004). Gruzelier (1998) investigated the dynamics of attentional systems in hypnotic states and identified a shift from left to right hemispheric processing, requiring interhemispheric integration. Those changes have been linked to shifts in attentional processing in frontal executive networks (Oakley & Halligan, 2013), highlighting the possibility that the frontoparietal propagation of cortical information observed in our data might reflect interhemispheric information integration related to attentional processing. Follow-up research should aim to clarify the function of interhemispheric frontoparietal information cascades in facilitating or sustaining hypnotic states.

4.3. *Neural markers of hypnosis did not distinguish levels of hypnotic depth*

An aim of our study was to utilize cortical markers of hypnotic states to discriminate levels of hypnotic depth. Our study revealed that manipulations of hypnotic depth resulted in a reportedly more intensive hypnosis-induced altered state of consciousness. Hypnotic deepening enhanced consciousness alterations manifesting in enhanced mental imagery, spiritual experiences, a sense of disembodiment, and a feeling of being one with the environment. Although we were able to elicit strong shifts in subjective experience, we did not find any evidence for a neural substrate underpinning any of those changes in experience between hypnotic states with different hypnotic depth. Hypnotic depth did not predict changes in neural markers across any of the neural candidate signatures

for hypnotic states (power spectrum, connectivity) chosen for this study. Numerous reasons might account for a lack of a link between hypnosis-related changes in experience and neural markers of hypnosis. First, hypnotic depth might influence brain activity patterns which were not included in the study or cannot be captured by EEG. Further research into the neural correlates of hypnotic depth using neuroscience methods with a higher spatial resolution such as fMRI and MEG is warranted to address this issue. Finally, our experimental design distinguishes two states of hypnotic depth, treating them as two distinct and steady states. Indeed, neural signatures of hypnotic depth are likely to fluctuate within a condition, leading to weaker cortical signals indexing hypnotic depth not being captured. Although levels of hypnotic states are mirrored in differences in experience ratings, only experiential differences between hypnotic states and the control condition might have been sufficiently large to manifest in strong cortical signal alterations. It is also a possibility that participants' prior beliefs about the impact of hypnotic depth on perception, cognition and emotion might influence their subjective reports. Since participants were aware which experimental condition they were in, those beliefs might cause subjective ratings of altered states of consciousness during HS2 to be inflated.

There is a controversy in hypnosis research over whether hypnosis is a distinct psychological state (state-theory of hypnosis) or a mere response to suggestion (non-state theory of hypnosis) (Hasegawa & Jamieson, 2002). State-theories of hypnosis posit that hypnotic induction leads to trance-like states which can vary in depth (Kahn & Allan Hobson, 2003; Kallio & Revonsuo, 2003; Kihlstrom, 2018; Pekala, 2015; Pekala & Levine, 1982; Rainville et al., 2002). Rooted in social cognitive psychology, non-state theories of hypnosis stipulate that hypnosis can be fully explained as a mix of attention, expectation, imagery, compliance, and role enactment without the need for trance (Graham, 1997; Jay Lynn et al., 2008; Kirsch et al., 2008; Sarbin & Andersen, 1967; Theodore, 1972; Barber, 1958), see Kihlstrom, 2018 for an overview. More recent views of conscious states support a central role for cognitive factors such as attention, expectation, and imagination (Chennu & Bekinschtein, 2012; Dehaene & Changeux, 2011; Hohwy, 2012; Posner, 1994). In line with previous work (Kallio & Revonsuo, 2003; Kihlstrom, 2018; Pekala, 2015; Pekala & Levine, 1982; Rainville et al., 2002; Timmermann et al., 2023), our research frames hypnotic states as altered conscious states. Hypnotic states manifest in neural activation influenced by attention and expectation (Cardeña, 2014; Jensen et al., 2017; Terhune et al., 2017). Although our experiment was not designed to disentangle both viewpoints, our results at the same time do not contradict the idea that social and cognitive factors play a role in hypnosis (Tuominen, Kallio, Kaasinen, & Railo, 2021). We propose that our results have implications for theories of altered conscious states. Prominent theories of conscious awareness stipulate that conscious perception is intimately connected to attention and that activity in frontoparietal attention-related networks indexes consciousness (Bekinschtein et al., 2009; Dehaene & Changeux, 2011; Dehaene & Naccache, 2001; Lau & Rosenthal, 2011). Framing hypnotic states as an altered state of consciousness, our finding that altered frontoparietal connectivity is linked to hypnotic states lends support to the notion that frontoparietal networks are involved in consciousness. Further research is needed to address whether interhemispheric information transfer in a frontoparietal network might play a general role in altered states of consciousness (e.g., psychedelic states, meditation, dreaming).

4.3.1. *Limitations*

A limitation of our study is the lack of population generalisability and comparability to previous studies. Since our study focused on phenomenal alterations during the hypnotic state, we recruited individuals with extensive experience in hypnosis rather than hypnosis-naive individuals. Our reason for recruiting individuals with extensive experience in self-hypnosis was to ensure the participants' familiarity with the hypnotic state. Based on work by Landry et al. (2017) and our own previous work (de Matos et al., 2023), our study design considers that trait-like hypnotic susceptibility cannot be equated with hypnotisation during the experiment. Since we recruited hypnosis experts, we did not collect information about hypnotic susceptibility (e.g., Harvard Group Scale). Research studies investigating the neural correlates of hypnotic states typically recruit hypnosis-naive participants, comparing highly and lowly susceptible individuals who are categorised based on results from a hypnotic susceptibility questionnaire (Landry et al., 2017; Terhune et al., 2017). We acknowledge that due to our study design in which we omitted hypnotic susceptibility ratings, the generalisability of our study to past work comparing highly and lowly hypnotisable participant groups is limited. Further studies are needed to examine whether the neural information measures tested in this study distinguish hypnosis-naive individuals with low and high hypnotic susceptibility. Unlike past work (Ciaramella, 2020; Kasos et al., 2022; Pekala & Creegan, 2020; Pekala & Kumar, 1986; Terhune & Cardeña, 2010), we used the CEQ which is based on the Phenomenology of Consciousness Inventory rather than the Phenomenology of Consciousness Inventory itself. Although this was necessary to reduce the duration of the experiment, it further limits the comparability of our study to previous experiments. Another limitation is that there is no blinding in our experimental design. Due to their experience with hypnosis, participants were always aware of which condition they underwent. As a result, participants' subjective reports might have been influenced by demand characteristics. Finally, a methodological limitation of our study is that sensor-space connectivity can be contaminated by volume artefacts (Aleksandra, Bailey, Vila-Rodriguez, Herring, & Fitzgerald, 2022; Jan-Mathijs et al., 2009; Domínguez, Wennberg, & Pérez Velázquez, 2007). Future work is needed to assess whether differences between both hypnotic states, as well as hypnotic and control states, might be associated with altered source-space connectivity.

In sum, our work contributes evidence to the theory that inter-hemispheric frontal mechanisms contribute to the neural basis of hypnosis. Although we substantiate the notion that frontal interhemispheric integration is linked to hypnosis, our study is compatible with different theories explaining frontal function in hypnotic states (such as attention, inhibition, top-down regulation). Future research needs to compare different frontal models of hypnosis within the same cohort

and experimental paradigm to evaluate which frontal model describes hypnotic states best. We also provide evidence for altered cortical information processing under hypnosis, reducing the influence of individual vertices over information flow across sensor-space. For a deeper understanding of the cortical dynamics supporting hypnotic states we identified in our study, we need further studies addressing how information flow sampled from the cortical surface during the hypnotic state might be driven by subcortical sources. Other future research avenues might address the time dynamics of hypnotic states, e.g., whether cortical signatures of hypnotic states change as you transition further into a hypnotic state. Ultimately, further research using spatially resolved neuroimaging methods might identify the neural basis of altered subjective experience elicited by manipulations of hypnotic depth.

Open practices section

The study in this article has earned Open Data and Open Materials badges for transparent practices. The data and materials studies are available at: https://osf.io/2gwnj/.

CRediT authorship contribution statement

Maria Niedernhuber: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Formal analysis, Conceptualization. **Aninka Charlotte Schroeder:** Data curation. **Céline Lercher:** Data curation. **Mike Bruegger:** Writing – review & editing, Resources, Project administration, Funding acquisition, Data curation, Conceptualization. **Nuno Miguel Prates de Matos:** Writing – review & editing, Resources, Project administration, Funding acquisition, Data curation, Conceptualization. **Valdas Noreika:** Writing – review & editing, Supervision. **Bigna Lenggenhager:** Writing – review & editing, Supervision.

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Supplementary data

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