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Changes in high-order interaction measures of synergy and redundancy during non-ordinary states of consciousness induced by meditation, hypnosis, and auto-induced cognitive trance

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ABSTRACT

High-order interactions are required across brain regions to accomplish specific cognitive functions. These functional interdependencies are reflected by synergistic information that can be obtained by combining the information from all the sources considered and redundant information (i.e., common information provided by all the sources). However, electroencephalogram (EEG) functional connectivity is limited to pairwise interactions thereby precluding the estimation of high-order interactions. In this multicentric study, we used measures of synergistic and redundant information to study in parallel the high-order interactions between five EEG electrodes during three non-ordinary states of consciousness (NSCs): Rajyoga meditation (RM), hypnosis, and auto-induced cognitive trance (AICT). We analyzed EEG data from 22 long-term Rajyoga meditators, nine volunteers undergoing hypnosis, and 21 practitioners of AICT. We here report the within-group changes in synergy and redundancy for each NSC in comparison with their respective baseline. During RM, synergy increased at the whole brain level in the delta and theta bands. Redundancy decreased in frontal, right central, and posterior electrodes in delta, and frontal, central, and posterior electrodes in beta1 and beta2 bands. During hypnosis, synergy decreased in mid-frontal, temporal, and mid-centro-parietal electrodes in the delta band. The decrease was also observed in the beta2 band in the left frontal and right parietal electrodes. During AICT, synergy decreased in delta and theta bands in left-frontal, right-frontocentral, and posterior electrodes. The decrease was also observed at the whole brain level in the alpha band. However, redundancy changes during hypnosis and AICT were not significant. The subjective reports of absorption and dissociation during hypnosis and AICT, as well as the mystical experience questionnaires during AICT, showed no correlation with the high-order measures. The proposed study is the first exploratory attempt to utilize the concepts of synergy and redundancy in NSCs. The differences in synergy and redundancy during different NSCs warrant further studies to relate the extracted measures with the phenomenology of the NSCs.

1. Introduction

A better understanding of the functional correlates of the effects of practicing non-ordinary states of consciousness (NSCs) on the brain may have medical, social, and scientific implications (Timmermann et al., 2022). NSCs have been reported to affect cognitive and psychosocial traits in individuals, thereby leading to better mental health.

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For example, meditation and hypnosis increase sleep quality and improve cognitive performance in reasoning, executive functions, working memory, and information processing (Cordi et al., 2015; Nagendra et al., 2012; Sulekha et al., 2006). Positive outcomes such as decreased anxiety and increased well-being due to practicing shamanic trance have been reported anecdotally (Sidky, 2009; Mackinnon, 2012; Grégoire et al., 2022). Resting-state functional magnetic resonance imaging (fMRI) studies have shown that NSCs affect state and trait-related neural changes and alter various brain functional regions associated with high-order cognitive processes such as emotion and attentional networks (Jiang et al., 2017; Froeliger et al., 2012; Farb et al., 2013). However, different NSCs, such as meditation, hypnosis and auto-induced cognitive trance (AICT), are associated with altering different brain functional networks, making it complex to understand the NSCs in a generalizable manner.

Meditation is an NSC where an individual has heightened self-awareness, alertness, and some control over thoughts (Dillbeck and Alexander, 1989; Travis, 2014; Lutz et al., 2016; Millière et al., 2018). It involves specific repetitive processes aimed at attaining unique states of consciousness and enhancing desired psychological qualities such as attention and empathy (Matko et al., 2021; Somaraju et al., 2023). The capability to respond to external suggestions but having an explicit intention not to respond to external stimuli or environment, which is the metacognitive access to intentions, is increased during certain types of meditation (Lutz et al., 2016; Lush and Dienes, 2019). Many studies have been conducted to investigate the state changes during Rajyoga meditation (RM) taught by the Brahmakumaris organization. In studies with electroencephalogram (EEG) involving an attentional task, change in mental states was faster (Nair et al., 2017), duration and frequency of the default mode network (DMN) microstates were higher (Panda et al., 2016) in long-term Rajyoga meditators than in non-meditators and short-term meditators. During RM, power in theta and alpha bands was higher (Sharma et al., 2018), as also the entropy in the frontal lobe in the gamma band (Kumar et al., 2021). On the other hand, delta activity (Sharma et al., 2023) and the distance between the covariance matrices of successive epochs (Ganesan et al., 2020) reduced compared to baseline conditions. Studies on trait changes reported a reduction in cortisol levels (Kiran et al., 2017), anxiety, chronic tension headache, obsessive-compulsive disorders (Kiran et al., 2017; Mehta et al., 2020; Amritsar, 2014; Arora et al., 2014) and stress caused by Covid-19, and increase in self-satisfaction (Ramesh et al., 2013), happiness scores (Babu et al., 2020), and better cardiorespiratory functions in Rajyoga meditators (Sukhsohale and Phatak, 2012) than in non-meditators.

Hypnosis, considered an NSC, is widely practiced by health care professionals in western countries and characterized by goal-directed focused attention, reduced peripheral awareness, and enhanced capacity for response to suggestion (Elkins et al., 2015). Four main components characterize hypnosis (Spiegel, 1991; Weitzenhoffer, 2002): absorption, dissociation, suggestibility and automaticity. Absorption is the tendency to become wholly involved in a perceptive or imaginary experience. Dissociation corresponds to a mental separation of components of behavior that generally are processed together. Suggestibility is the tendency to conform to the suggestions given and to suspend one's critical judgment, with increased involuntary and decreased control of thoughts. Automaticity is the nonvoluntary response to suggestions. Increase in duration and occurrence of specific EEG microstates (Katayama et al., 2007), increased connectivity in DMN-related networks (Demertzi et al., 2011), and higher segregation and integration (Panda et al., 2023) have been found during hypnosis.

AICT was introduced by the Trancescience Research Institute based on shamanic mongolian tradition. AICT is induced via vocalizations and body movements. It is characterized by an altered sense of self, lucid but narrowed awareness of the environment, enhanced inner imagery, and a modified somatosensory processing (Flor-Henry et al., 2017; Grégoire et al., 2022). A few case studies of trances inherited from shamanic traditions, including AICT, showed neurophysiological association (EEG, MRI) with subjective changes in body awareness, emotional state, and thinking, with dissociation from and modulation of perceptions of the environment, and visual imagery (Hove et al., 2015; Flor-Henry et al., 2017; Kawai et al., 2017; Mainieri et al., 2017; Gosseries et al., 2020; Huels et al., 2021). Neurophysiological study of one subject with extensive training in AICT displayed increased EEG coherence in the left hemisphere, decreased coherence in the right hemisphere in the low beta band, and increased anterior-posterior coherence in the high beta band (Flor-Henry et al., 2017).

Studies on EEG functional connectivity (FC) have a limited scope since they are measures of pairwise interactions, thereby neglecting the high-order interactions involving more than two sources. Interdependencies give information on what makes the system more effective as a whole than when considered in parts (Crutchfield, 1994). High-order interdependencies are the key to understanding complex systems such as the brain (Battiston et al., 2021; Rosas et al., 2019). High-order interaction methods such as integrated information theory and partial information decomposition (PID) are motivated by the study extending the characterization of information interaction among larger groups of sources (McGill, 1954). PID is considered a promising approach in studying high-order interdependencies that distinguish the types of information that the source variables convey about a target variable (Tononi et al., 1994; Williams and Beer, 2010; Griffith and Koch, 2014; Wibral et al., 2017). The high-order interactions extracted using PID are revealed by the measures of synergy and redundancy that play essential roles in information processing through neural dynamics (Luppi et al., 2022). Redundant interactions refer to information shared or highly correlated between three or more variables (Rosas et al., 2018). By contrast, synergy corresponds to information that can only be obtained by considering all the variables and not using any subset of variables (Rosas et al., 2019; Wibral et al., 2017; Timme et al., 2014). Synergy allows independence locally and integration globally to coexist, which is now considered significant for enabling higher-order brain functions (Luppi et al., 2022).

Highly synchronized activity, such as epilepsy and deep sleep stages, has higher redundancy than ordinary conscious/wakeful state (Tononi and Edelman, 1998; Tononi et al., 1994). Literature on neural coding has demonstrated the utility of the concepts of synergistic and redundant information and their role in information processing (Schneidman et al., 2003; Latham and Nirenberg, 2005). In addition to unique information available from all the sources, multiple sources may also carry redundant and synergistic information. The system may not be able to perform the computations for cognition only by having multiple copies of the information (redundant); it also requires information to be collated (synergistic) to enable cognition, thus providing fundamental insights about the brain's information processing architecture (Luppi et al., 2022).

The domain of synergistic and redundant interdependencies in the brain has relatively been unexplored against the space of bivariate functional connectivity analysis (Varley et al., 2023). Evidence is currently lacking to establish the role of synergy and redundancy in consciousness studies. The PID method used in the present study is based on extending Shannon's mutual information to the multivariate case (Watanabe, 1960; Sun, 1975; Williams and Beer, 2010; Tononi et al., 1994). The necessary mathematical background has been developed recently by Rosas et al. (2019). O-information provides measures of synergistic and redundant interactions between groups of more than three electrodes (Rosas et al., 2019). This has led to using these measures in finding synergistic and redundant cores or subsystems in the human brain in healthy ageing (Gatica et al., 2021), information exchange in neuronal circuits (Stramaglia et al., 2021), and interactions in music composition (Scagliarini et al., 2022). Our study goes in a similar direction to reveal the changes in high-order interactions during NSCs, which may offer insights into the cognition involved during different NSCs. Using EEG recorded during NSC conditions during RM,

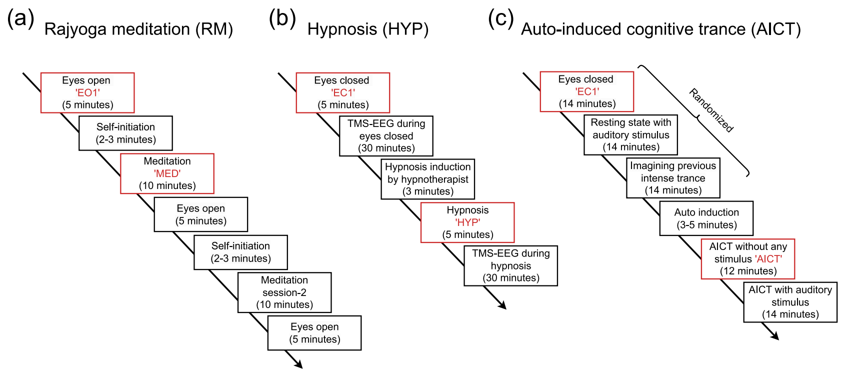

Fig. 1. Experimental protocol: (a) Meditators performed Rajyoga meditation (RM) in two sessions with an intermediate baseline between the sessions. Both RM and the baseline happened with the eyes open. (b) Participants underwent a hypnotic experience after the initial eyes-closed condition. (c) Participants of auto-induced cognitive trance (AICT) session with and without auditory stimulus, after the initial eyes-closed rest. Both hypnosis and AICT sessions happened with eyes closed. The blocks marked in red color are the segments included in the study.

hypnosis, and AICT and their respective baseline (ordinary state of consciousness), the changes in high-order interactions during these NSCs are examined. Specifically, we study how synergy and redundancy vary in the NSCs and attempt to supplement our understanding of the NSCs using other analytical measures.

2. Materials and methods

2.1. Data collection

2.1.1. Rajyoga meditation (RM)

A cohort of 26 healthy Hindi-speaking long-term Rajyoga meditators was recruited for the study (Kumar et al., 2021). The meditators were recruited based on age (25 to 60 years) and years of practice (greater than 5 years of frequent practice). EEG recording was conducted at the Indian Institute of Science, Bangalore, India. The experimental room was maintained with low light appropriate for meditation. Each participant could choose to sit on a comfortable chair or recliner. As shown in Fig. 1a, the experiment consisted of an eyes-open ordinary state of consciousness session for around 5 min followed by an eyes-open RM session for 10 min. The RM session considered in the study involves focusing on oneself as a point source of light at the center of the forehead and considering oneself as a peaceful being (called a soul-conscious state) (Ramsay et al., 2010). In this state, meditators focus their thoughts on themselves and their original qualities and consider peace to be their strength. The post-meditation baseline was recorded for 5 min with eyes open after they stopped meditating and returned to ordinary consciousness. This baseline was followed by a stage called the angelic state (BrahmaKumaris, 1994), where they engage in thoughts of good wishes for the universe for 10 minutes. This was followed by a final baseline of 5 min with eyes open. All the meditators were informed to practice both the above types of meditation for 10 min each for a week before the experiment to make the study uniform. The subjects could maintain minimum movements during the recordings. EEG data was recorded using a gel-based 64+3 (ECG, respiration, galvanic skin response) channel ANT Neuro amplifier system with a 10–10 system waveguard cap. The data were sampled at 1024 Hz and referenced to the CPz electrode. All the electrodes were maintained at less than 5 kΩ impedance. Four subjects were excluded from the study due to insufficient data quality and the shorter length of the data available, resulting in a total of 22 subjects (two females) aged 32 to 50 years (mean age: 44 ± 4.5 years) with a mean RM experience of 22.7 ± 5.6 years. For the present study, baseline (EO1) and initial meditation (MED) sessions of Rajyoga practice data were considered. The experimenter asked the meditators about the quality of their meditation session, and all the subjects reported the quality of meditation as good.

2.1.2. Hypnosis

The hypnosis dataset was recorded at the University Hospital of Liège in Belgium from 12 highly hypnotizable (according to the Stanford Hypnotic Susceptibility Scale, form C (Weitzenhoffer and Hilgard, 1962) and the Hypnosis Liège Scale (Vanhaudenhuyse et al., 2019)) French-speaking subjects (Panda et al., 2023). The subjects were instructed to sit on a comfortable chair with the freedom to stretch their legs. The experimental room was maintained with low light. EEG was recorded during 5 min of ordinary conscious state with eyes closed (EC1) followed by a hypnosis session with eyes closed (Fig. 1b). Hypnosis was conducted by an anesthesiologist, an expert in hypnosis (MEF). Participants underwent hypnosis with an induction technique used in clinical practice consisting of eye fixation with progressive muscle relaxation for 3 min. Suggestions of increased sensation of relaxation by closing the eyes were then made to the subjects to allow them to experience neutral hypnosis (i.e., to deepen their experience by listening to white noise output from a speaker) without any specific suggestion (Vanhaudenhuyse et al., 2019). The hypnotic (HYP) state with minimum movement was maintained for approximately 5 min, along with white noise. The dataset included both resting state EEG and TMS-EEG recordings as shown in Fig. 1b.

TMS-EEG recording was carried out to investigate brain complexity using perturbational complexity index (Casali et al., 2013) and is out of the scope of this study. TMS was designed to have minimal and transient effects on brain activity. Any immediate disruptions were short-lived and did not significantly interfere with subsequent recordings (Leodori et al., 2022; Casarotto et al., 2010). The self-reporting questionnaire was collected from the subjects, including questions on absorption and dissociation scored on a visual analogue scale from 0 to 10. EEG data was recorded with a saline-based 60+4 (2 electrodes on the forehead for ground and reference and two on the face for EOG) channel Nexstim amplifier with a 10–10 standard electrode system cap. The data were sampled at 1450 Hz and were referenced to the electrode placed on the forehead. All the electrodes were maintained at less than 5 kΩ impedance. Three subjects were excluded from the analysis due to technical issues during data recording. Nine subjects (six females) aged 19 to 29 years (mean age: 24 ± 3 years) were included in the study, which considered only the baseline (EC1) and hypnotic session (HYP) recordings.

2.1.3. Auto-induced cognitive trance (AICT)

Data from 27 French-speaking participants were considered for the present study. The data was recorded at the University and the University Hospital of Liège in Belgium. All the participants underwent a sound loop-based training developed by C.S., one of the co-authors who is an expert in AICT, and the TranceScience Research Institute (https://trancescience.org/). After this training, the participants could practice

AICT and remain without movement during the state. The original experimental protocol consisted of five conditions (refer Fig. 1(c)): resting state with eyes closed ('EC1'); ordinary state of consciousness with eyes closed and auditory stimulus ('aud'); imagining a previous intense AICT session but not entering into AICT state ('imag'); AICT as they practice daily ('AICT'); and AICT with auditory stimuli ('aud-AICT'). The conditions 'EC1', 'aud', and 'imag' were counterbalanced, while the conditions 'AICT' and 'aud-AICT' were in sequence after the first three conditions. The EEG data were recorded with a saline-based electrode-net EGI Geodesics system with 256 channels at a sampling rate of 500 Hz. Six subjects were excluded from the analysis due to insufficient data quality or missing channels, resulting in 21 subjects (17 females) with ages ranging from 23 to 68 years (mean age: 43.6 ± 12.4 years). Baseline (EC1) and AICT sessions only were included for the present study. Self-reporting questionnaires were collected from the subjects including questions on absorption and dissociation scored on visual analog scale from 0 to 10. The questionnaire relating to absorption and dissociation used for hypnosis and AICT is shown to be a good indicator to characterize the subjective experience of NSCs in healthy volunteers (Vanhaudenhuyse et al., 2019). In addition, this questionnaire has been used in several peer-reviewed studies related to NSC (Rousseaux et al., 2023; Martial et al., 2019; Demertzi et al., 2015). In the AICT dataset, participants were also asked to report if they entered into a trance (yes/no), and if yes, they were asked to rate the intensity of the trance on a scale from 0 (no trance) to 10 (most intense trance). All AICT participants reported entering the trance and the mean intensity was 6.14 ± 2.25. These participants also completed the revised Mystical Experience Questionnaire (MEQ) comprising 30 questions (Barrett et al., 2015).

The baseline and intervention recordings for each dataset were collected under the same conditions of eyes open or closed. Since RM was practised with the eyes-open (EO) condition, the baseline was also recorded with eyes open. Hypnosis and AICT were performed with eyes closed (EC), and hence, the baselines were also recorded with eyes closed. The study by Barry et al. (2007) reported a significant decrease (at $p \leq 0.001$) in delta, theta, alpha, and beta bands during EO compared to EC conditions with topographic changes implying the cortical processing of visual input during EO condition. Another study (Barry and De Blasio, 2017) involving healthy young and older adults reported decreased delta (at $p \leq 0.01$), theta (at $p \leq 0.01$), and alpha power (at $p \leq 0.001$) in older adults during the EC condition, and these differences were not observed during the EO condition. Hence, we only report the within-group changes, for which the recording conditions and set-up were identical and only within-group changes were subjected to a significance test.

To assess the relation between phenomenology and its putative cortical correlates, Pearson correlations were estimated between the high-order interaction measures and absorption, dissociation (hypnosis and AICT datasets) as well as the MEQ (based on the five factors from the AICT dataset). Self-reported ratings from 0 (none) to 5 (extreme) for each of the five factors of MEQ were considered from 21 subjects. Factor scores were computed by calculating the average response to the respective items (Barrett et al., 2015). 15 questions were related to mystical, six to positive mood, six to transcendence of time, three to ineffability and total score.

The respective experiments were approved by the Institute Human Ethics Committee of the Indian Institute of Science (RM dataset: 02/20201126) and the Ethics Committee of the Faculty of Medicine of the University and University Hospital of Liège (Hypnosis dataset: 2012/55, AICT dataset: 2019/141). Informed consent was obtained from each subject before enrollment in the respective study. There were no common subjects between different NSCs, and the subjects of one NSC were naive to the other NSC technique.

2.2. EEG data processing

The datasets were preprocessed with a standard pipeline using custom MATLAB (The MathWorks Inc., ver 2020b) scripts based on EEGLAB (Delorme and Makeig, 2004) and associated plugins. A high-pass filter with a 1 Hz cutoff was applied to the EEG time series. The data was then notch-filtered at 50 Hz with a bandwidth of 2 Hz to remove the line noise. The bad channels and segments were detected using a custom-written code. The bad segments detected were removed, and bad channels were interpolated using the spline interpolation method. Then independent component analysis (ICA) was applied using the runica algorithm (Makeig et al., 1997) to remove eye movement artifacts. ICA components related to artifacts were then rejected manually, and the bad segments in the data not identified by the preprocessing pipeline were detected and removed by visual inspection from the continuous data. In RM dataset, out of 64 electrodes, mastoid electrodes M1, M2, and the reference electrode CPz were not included for analysis, resulting in 61 electrodes. In the hypnosis dataset, out of 60 electrodes, the inion (Iz) electrode was excluded from the analysis, resulting in 59 electrodes. The Iz electrode was excluded since I1 and I2 electrodes were not part of the montage. In the AICT dataset, 68 EEG channels were selected based on the Geodesics layout (Luu et al., 2011). The datasets were re-referenced to the common averaging scheme and were downsampled by integer factors to 128 Hz (RM dataset, decimated by a factor of 8), 131 Hz (hypnosis dataset, decimated by a factor of 11), and 125 Hz (AICT dataset, decimated by a factor of 4). The maximum difference in the sampling rate across datasets was 6 Hz (47 ms). The data were then bandpass filtered into delta (1–4 Hz), theta (4–8 Hz), alpha (8–12 Hz), beta1 (12–20 Hz), beta2 (20–30 Hz), slow gamma1 (30–38 Hz) and slow gamma2 (38–45 Hz) frequency bands for further analyses. 4 minutes each of data were considered for the baseline and each NSC condition. One value of synergy and one value of redundancy were obtained from the entire 4-min segment of data for each electrode.

3. Synergy and redundancy analysis

We used the O-information (shorthand for information about organizational structure) to quantify the intrinsic statistical redundancy and synergy in groups of 5 variables (i.e., EEG signals) (Rosas et al., 2019; Scagliarini et al., 2024, 2022). O-information is a real-valued measure whose sign discriminates between synergistic and redundant components. S-information (shorthand for the strength of the interdependencies) is also measured, which complements O-information. The details of estimating O-information and S-information are given in the supplementary section. Studies in the past mostly derived synergy and redundancy from two or three sources of information (Erramuzpe et al., 2015). In the current study, we explored different orders (number of EEG channels considered at a time, $n = 3, 4, 5$), and $n = 5$ was decided considering the number of combinations required to calculate O-information, which increases exponentially with n, making it practically impossible for n greater than 5 (Gutknecht et al., 2021). This is a novelty in the studies on NSCs and may be considered a methodological improvement. Taking $n = 5$, the AICT dataset with 68 channels resulted in ${}^{68}C_5 = 1.0424128 \times 10^7$, the RM dataset with 61 channels in ${}^{61}C_5 = 5.949147 \times 10^6$, and the hypnosis dataset with 59 channels in ${}^{59}C_5 = 5.006386 \times 10^6$ combinations to evaluate the O-information.

4. Statistical analysis

The non-parametric two-tailed Wilcoxon signed rank-sum test (Hollander et al., 2013) was applied to the extracted measures for a significance level of $p < 0.05$. The data was band-pass filtered into different frequency bands before extracting the high-order measures of synergy and redundancy. For a frequency band of interest, the statistical significance of the change in high-order measures was tested with electrodes and conditions. Hence, the false discovery rate (FDR) correction for multiple comparisons was applied across electrodes and not across different frequency bands using the standard procedure proposed by Benjamini and Hochberg (1995). The age ranges of the subjects were checked across the datasets using the Wilcoxon rank-sum test (Woolson, 2007) for significant differences.

5. Results

5.1. RM dataset

The synergy patterns were distinct across the different bands, as shown by Fig. 2(a) and Supplementary Fig. 2(a). Synergy significantly increased during RM at the whole brain level in the delta (critical p = 0.032) and theta bands (critical p = 0.026), as shown by Fig. 2a. Global mean synergy was significantly higher in delta (p = 0.01) and theta (p = 0.001) bands, as shown by Fig. 4a, than the baseline condition. Redundancy significantly decreased in the delta band (critical p = 0.033) in frontal, right-central, parietal, and occipital electrodes, and in beta1 (critical p = 0.039) and beta2 (critical p = 0.036) bands in frontal, central, and posterior electrodes as shown by Fig. 3. Global mean redundancy of the meditators significantly decreased in delta (p = 0.01), beta1 (p = 0.004) and beta2 (p = 0.003) bands as shown by Fig. 4(b), compared to their baseline condition.

A non-significant increase in synergy was found in the left fronto-central and posterior electrodes in the alpha band. This non-significant increase was confined to left-frontal and posterior electrodes in beta2, sGamma1, and sGamma2 bands (Supplementary Fig. 2(a)). This general trend of non-significant increase in synergy in alpha and slow gamma bands is reflected in the mean synergy plots shown in Fig. 4(a). Unlike the case of synergy, the patterns of change (significant or non-significant) in redundancy were consistent across different frequency bands, and predominant changes were observed in the frontal and posterior electrodes (Fig. 3 and Supplementary Fig. 3(a)). The trend of a non-significant decrease in global mean redundancy was observed in all other frequency bands, as shown by Fig. 4(b). Significant increase in mean S-info was observed in theta band during RM as shown by Fig. 4(c).

5.2. Hypnosis dataset

Synergy decreased during hypnosis in several bands with varied statistical significance. A significant decrease in synergy during hypnosis was found in mid-frontal, temporal, and mid-centro-parietal electrodes in the delta band (critical p = 0.011) and in left frontal, right-parietal electrodes in beta2 (critical p = 0.011) band as shown in Fig. 2(b). Reduction in global mean synergy was significant in delta (p = 0.01), theta (p = 0.03), alpha (p = 0.03), beta1 (p = 0.02) and beta2 (p = 0.01) bands as shown in Fig. 4(d).

Distinct patterns were observed in synergy values across different bands, as shown in Fig. 2(b) and Supplementary Fig. 2(b). Mean S-info showed a non-significant decreasing trend during hypnosis across the delta, theta, alpha, and beta1 bands, as shown in Fig. 4(f). No significant differences were found in redundancy in any of the bands considered after correcting for multiple comparisons. Although non-significant, a common pattern was generally observed in redundancy across all bands and conditions (Supplementary Fig. 3(b)). Redundancy values were higher in the frontal electrodes, excluding the midline electrodes, as shown in Supplementary Fig. 3(b). Global mean redundancy across all electrodes in different frequency bands showed no changes during hypnosis, as shown in Fig. 4(e). Differences in high-order measures between EO1 and EC1 of the hypnosis dataset are given in Supplementary Figs. 4(a) and (b). Compared to EO, synergy decreased in delta and theta bands and increased in alpha and higher bands during EC. Similar results were observed with redundancy during EC in delta and theta bands but an increase in frontal and decrease in posterior regions were observed in beta2 and gamma bands compared to EO.

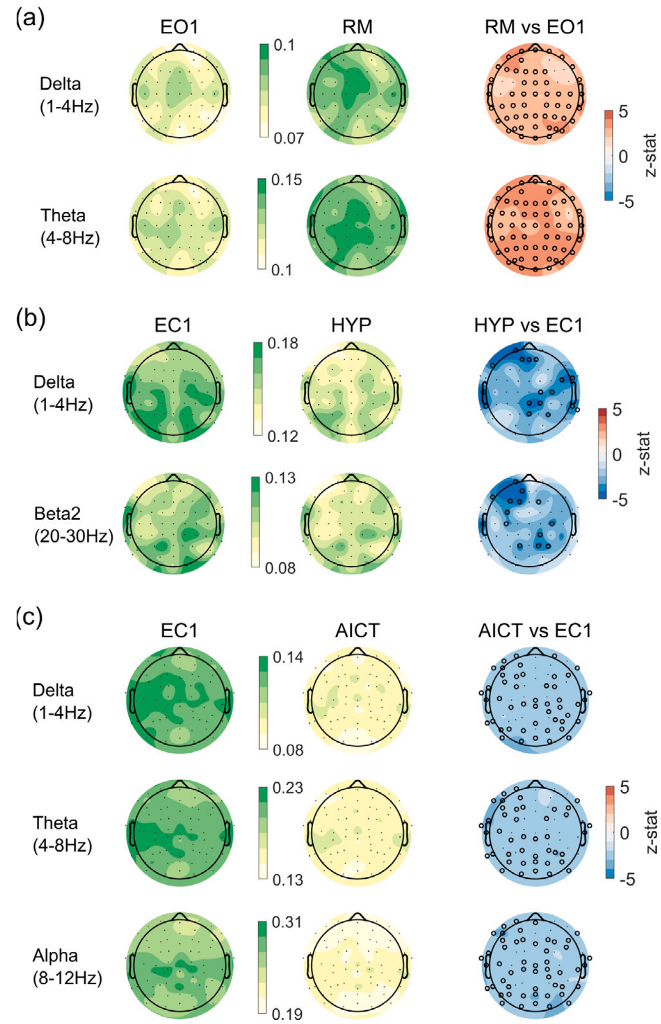

Fig. 2. Baseline values of synergy and changes during the three NSCs. (a) Rajyoga meditation (RM), in delta and theta bands; (b) Hypnosis (HYP), in delta and beta2 bands; (c) auto-induced cognitive trance (AICT), in delta, theta, and alpha bands. Left column: during baseline condition with eyes open or closed as the case may be. Middle column: during the NSC with the same scale; Right column: change in synergy during NSC compared to baseline with same z-statistic scale across all bands. The circles in the last column denote the statistically significant electrodes after correction for multiple comparisons across electrodes.

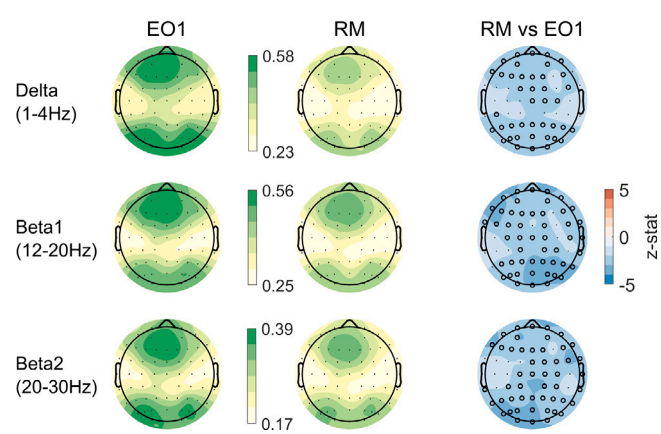

Fig. 3. Redundancy values of meditators in delta, beta1, and beta2 bands. Left column: during eyes-open baseline condition; Middle column: during Rajyoga meditation (RM) with eyes open with same scale; Right column: change in redundancy during RM compared to baseline with same z-statistic scale across all bands. Circles in the third column denote the statistically significant electrodes after correction for multiple comparisons across electrodes.

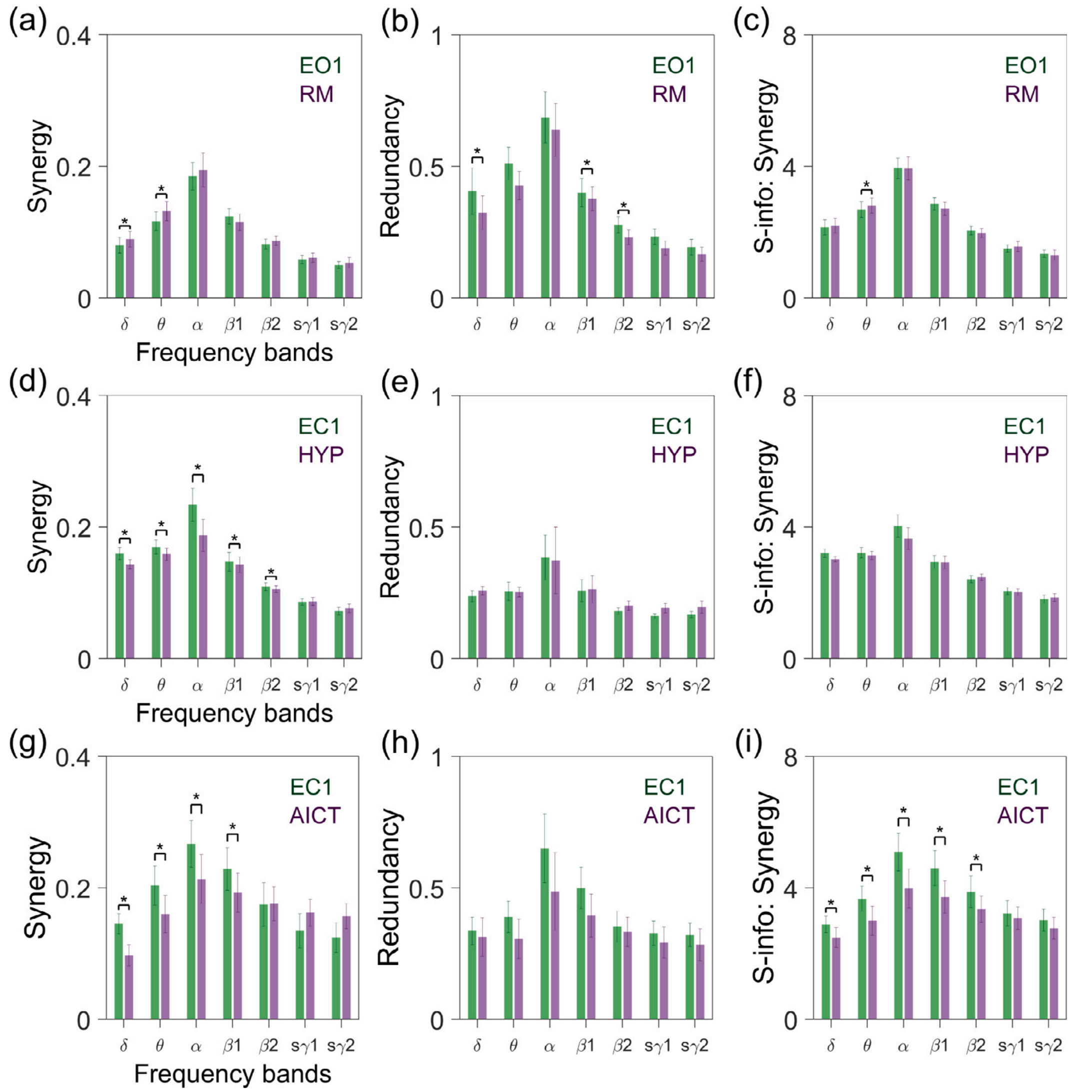

Fig. 4. Changes in global mean synergy and redundancy across all electrodes in different EEG frequency bands in Rajyoga meditators (top row), volunteers undergoing hypnosis (middle row), and during AICT (bottom row). Global mean synergy values (a), (d), (g). Global mean redundancy (b), (e), (h). Global mean structural information (S-info) obtained for synergy n-plets (c), (f), (i). Stars represent the statistical significance after multiple comparison corrections at $p < 0.05$.

5.3. AICT dataset

Distinct patterns were observed in synergy values across different bands, as shown in Fig. 2(c) and Supplementary Fig. 2(c). As shown in Fig. 2(c), synergy decreased during AICT in the left-frontal, right-frontocentral, and posterior electrodes in delta (critical p = 0.017) and theta bands (critical p = 0.015). A decrease in synergy was observed at the whole brain level in the alpha band (critical p = 0.019). No significant changes in synergy were observed in other bands. The difference in mean global synergy between baseline EC1 and AICT conditions was significant in delta (p = 0.006), theta (p = 0.008), alpha (p = 0.004), and beta1 (p = 0.01) bands as given in Fig. 4(g). Mean S-info followed the trend of synergy and was significant in delta (p = 0.003), theta (p = 0.002), alpha (p = 0.001), beta1 (p = 0.003), and beta2 (p = 0.01) bands as shown in Fig. 4(i).

A trend of non-significant decrease in synergy values was observed in slow gamma bands, as shown in Fig. 4(i). Although the change in redundancy was not significant, a general trend of decrease in redundancy was observed during AICT across all the frequency bands, and the magnitude of reduction was higher in delta, theta, alpha, and beta1 bands as shown in Supplementary Fig. 3(c) and Fig. 4(h).

The results of different NSCs are summarized in Table 1. Due to the disparities in the mean age of hypnosis from RM and AICT datasets, direct comparison of synergy and redundancy measures across datasets are not reported. The study limitations are given in Table 2.

5.4. Additional analysis

The correlation between the synergy values and the values of absorption and dissociation reported by the subjects and their significance values are given in Supplementary Table 1. We did not find any significant correlation in any of the frequency bands in both hypnosis and AICT subjects. No behavioral scores were available for the RM data. As already explained above, all three datasets were independently recorded as part of distinct experiments. Based on our analysis, we found that the hypnosis group was significantly younger than RM and AICT groups ($p \leq 1.41 \times 10^{-5}$).

Pearson correlation between age and change in extracted measures were estimated in the three datasets for the bands that showed significant changes between baseline and NSC conditions. The results are given in Supplementary Table 2. No significant correlations were observed across datasets and bands. The results imply that the change in synergy and redundancy during NSCs are independent of age. Supplementary Table 3 lists the correlation and p-values (linear fit) between MEQ factors and the change in the high-order measures (synergy and

Table 1
Summary of the main findings, indicating the significant changes in synergy and redundancy for each NSC, from its respective baseline condition. RM: Rajyoga meditation, HYP: Hypnosis, AICT: Auto-induced cognitive trance. ↑: increase in the value of the metric during NSC relative to its baseline. ↓: decrease in the value of the metric during NSC relative to its baseline.

	Synergy			Redundancy		
	RM	HYP	AICT	RM	HYP	AICT
DELTA	↑ whole brain level	↓ mid-frontal, temporal, mid-centro-parietal electrodes	↓ whole brain level	↓ frontal and posterior electrodes	– –	– –
THETA	↑ whole brain level	–	↓ whole brain level	–	–	–
ALPHA	–	–	↓ whole brain level	–	–	–
BETA1	–	–	–	↓ whole brain level	–	–
BETA2	–	↓ left frontal, right- parietal electrodes	–	↓ whole brain level	–	–

redundancy) during AICT. Out of 21 subjects, 3 subjects reported strong, 5 reported moderate, 2 subjects reported slight mystical experience, 6 subjects reported slight but cannot decide about the mystical experience and 5 subjects reported not had a mystical experience. Mystical experience, with mean and standard deviation across subjects being 2.31 ± 1.61, PostiveMood with 2.51 ± 1.28, Transcendence of Time with 3.28 ± 1.34, Ineffability with 3.49 ± 1.34, and Total score with 2.38 ± 1.3. No significant correlations were observed between synergy or redundancy and any of the MEQ factors mentioned above.

As a control analysis, shuffling the time samples within the segments was not carried out as the synergy and redundancy measures were extracted from the distribution of the samples, and the entire 4-min data was considered to extract the measures. However, for sanity check, data shuffling between EO and NSC conditions was carried out within all the datasets, and no significant changes were observed in the values of the synergy and redundancy measures. Finally, the datasets were shuffled across RM and hypnosis datasets, and once again, no significant changes were observed.

6. Discussion

Rosas et al. (2019) published their algorithm for quantifying high-order interdependencies via multivariate extensions of the mutual information only recently, and hence, interpretations of the values of synergy and redundancy in terms of brain function are in their infancy. Further, to the best of our knowledge, this study is the first to measure synergy and redundancy in three NSCs, applied across sets of five electrodes. Our findings show increased synergistic interdependencies in delta and theta bands during RM. On the other hand, synergy decreased in delta and beta2 bands in selected regions during hypnosis and in the delta, theta, and alpha bands during AICT. Table 1 summarizes the significant changes observed in the synergy and redundancy values in the different frequency bands for each NSC. A decrease in redundant interdependencies in delta, beta1, and beta2 bands was observed during RM, whereas no significant changes were observed in redundancy during hypnosis or AICT with respect to their baseline values. Behavioral measures, including absorption, dissociation and mystical experience, did not show any significant correlation with the high-order interaction measures.

The study brings novelty in two key aspects. Investigating three distinct NSCs, namely RM, hypnosis, and AICT is novel, and we independently looked at how high-order interaction measures were altered across the brain regions during the practice of each of them. The proposed study is the first to apply synergy and redundancy measures using O-information on EEG with more than three electrodes. In the studies reported in the literature, the measures of high-order interaction, namely synergy and redundancy, were mostly derived from two or three sources of information.

6.1. Brain has complex and emergent behavior

Rosas et al. (2018) reported that higher redundancy and lower synergy values are associated with complex and emergent behaviors in certain cellular automata. The current study showed that the range of redundancy values was always higher than the range of synergy values across all frequency bands and datasets. A similar observation was made in the fMRI study by Gatica et al. (2021), where they opined that the trend could be different in EEG or MEG studies. Thus, our results confirm that the relative differences in the range of values of the high-order interaction measures are characteristic of the human brain, which is predominantly redundant in the information carried by EEG or fMRI.

6.2. Synergy in delta and theta bands

The delta band plays a role in inhibiting the sensory afferents that interfere with internal concentration, thereby supporting mental tasks (Harmony, 2013). Thus, increased synergy and decreased redundancy during RM in the delta band at the whole brain level may be related to increased self-awareness. It may imply increased interdependencies (high-order interactions) involving information exchange across different brain areas. A decrease in synergy in the delta band during AICT may, therefore, be a reflection of the reduced awareness that characterizes AICT. Theta activity reflects affective processing and orienting (Aftanas and Golocheikine, 2001; Langer et al., 2013). Hence, increased synergy in the theta band during RM may imply increased awareness and internal focus. The decreased synergy during AICT in the theta band may indicate decreased awareness and a modified sense of self. Functional alpha (distinct from the spontaneous alpha, which is maximum during eyes closed condition) has been observed during sensory and cognitive processes (Başar et al., 1999). Distributed and selective functional alpha oscillations are associated with increased levels of cognitive input (Başar et al., 1999). The reduced synergy during AICT in the alpha band may then imply altered sensory perception.

In a study using intracranial EEG (Bauer et al., 2022), large common connectivity patterns were observed in lower frequencies during both hypnosis and mindfulness sessions compared with mind-wandering (baseline) sessions of the same subjects. While meditation is associated with enhanced metacognitive access to intentions, hypnosis involves experiencing a sense of automaticity and inaccurate metacognition about intentional actions (Lush and Dienes, 2019). A decrease in synergy in delta and theta bands during hypnosis and AICT may suggest reduced awareness of the environment and a modified sense of self, except that we did not find any correlation with the behavioral scores. A study with a highly hypnotizable subject reported decreased remote functional connections in delta activity across different cortical regions, suggestive of increased independent brain processing to maintain alertness required during hypnosis (Fingelkurts et al., 2007). The same study speculated that communication between the thalamus and cortex was disrupted to an extent during hypnosis. Another study on a highly hypnotizable subject reported that coherent activity reduced in frontoparietal regions during a single-word hypnotic induction with transcranial magnetic stimulation, which could be related to the present results of reduced synergy during hypnosis (Tuominen et al., 2021).

Beta oscillations have been linked to sensorimotor processing and attention (Engel and Fries, 2010). Studies have reported decreased beta

Table 2
Main limitations of the current study.

#1	Direct comparison of high-order measures extracted across the three NSC datasets (RM, hypnosis, AICT) is precluded notably because of disparities in the mean age of HYP from RM and AICT datasets and gender differences between the datasets. Upon analysis, correlating synergy and redundancy measures with age yielded non-significant results across all datasets, as shown in Supplementary Table 2. This indicates that changes in high-order measures during NSCs are age-independent, warranting further investigation with age and gender-matched subjects in hypnosis dataset. Nonetheless, future research should address the extent to which observed variations may stem from gender, geographical and cultural differences between the datasets.
#2	No common questionnaires were collected across the three datasets. No behavioral questionnaires except the quality of meditation sessions were collected in the RM protocol. However, common questionnaires were used while collecting hypnosis and AICT data. Due to the unavailability of the questionnaires in the RM dataset, establishing the inter-relations between the NSCs has not been attempted in the current study.

activity in parietal cortices during meditation and cortical inhibition during selective attention (Faber et al., 2015). Decreased synergy in the beta band during hypnosis could be due to altered sensorimotor processing due to the hypnotist's suggestions. Decreased redundancy in beta1 and beta2 bands during RM may imply the facilitation of selective attention. More redundancy implies that the same information is simultaneously available in more than two areas, suggesting ineffective utilization of the available resources. It does not necessarily imply increased connectivity. We did not find any significant correlation between brain metrics and behavioural measures. This could be due to the small sample size or the chosen phenomenological variables.

6.3. Decreased redundancy, cognitive functions, and broadcasting

Luppi et al. (2022) demonstrated the existence of a synergistic workspace of brain regions involving prefrontal and parietal regions that are critical in executing cognitively demanding functions. The increase of synergy in RM and decrease in hypnosis and AICT in specific bands in the parietal regions align with the observations of the above study. In another work, Luppi et al. (2020) distinguished gateways that bring information from localized modules to the workspace and broadcasters that disseminate information from the workspace to the low-level regions. The observed global decrease in redundancy in delta, beta1, and beta2 bands during RM and a non-significant decreasing trend during AICT may imply the reduced role of broadcasters. This reduced role of broadcasters may be due to the conscious decision of an individual not to react to external stimuli while meditating or in AICT, which is not the case during hypnosis where the subject is under suggestion instructions and require reacting to the external stimuli.

Table 2 summarizes the key limitations of the study. The ages of RM and AICT subjects were not significantly different, and the synergy results may be considered ruling out age as a factor. The data considered in the study were recorded using different amplifiers and in different labs. Synergy and redundancy changes have been exclusively analyzed within each dataset and not compared across different datasets. Given the normalization step employed by various EEG amplifiers before extracting recorded data, it is reasonable to assert that EEG comparisons remain valid, mitigating concerns regarding amplifier variations. Previous studies have demonstrated comparable signal-to-noise ratios among amplifiers (Pattisapu and Ray, 2023), the minimal impact of the instrument and thermal noise affecting higher frequency bands (≥100 Hz) (Scheer et al., 2005). However, the current study focuses on low-frequency oscillations, including the slow-gamma band. Hence, concerns regarding amplifier differences across the three datasets are deemed negligible. In the future, we intend to study different NSCs practised by age and gender-matched cohorts recorded with identical amplifiers and specifications to rule out these potential confounding factors. In the current circumstances, it is unavoidable that interpretations of the changes in these measures and the discussion will appear somewhat speculative. The authors also are interested in deepening the interpretation of the results. Only after considerable further research applying these high-order interaction metrics on EEG, the role and interpretation of these measures will become unambiguous and clear. However, we may need more studies with common questionnaires and deciding upon the relevant parameters related to phenomenology, which may correlate well with the extracted measures. Ideally, the same variables will be investigated for all NSCs.

7. Conclusion

Summarizing, the increase of synergy in the delta band during RM may be related to the increase in self-awareness and is further substantiated by the decrease of synergy in the delta band during hypnosis and AICT, under both of which self-awareness decreases. However, the behavioral scores which did not capture the self-awareness component did not correlate with synergy. The results show the balance of synergy and redundancy during different NSCs. By dissecting the intertwined roles of synergy and redundancy in the interactions between brain regions offers a robust method to capture the cognition involved during NSCs, surpassing traditional FC measures which fail to address high-order interactions. We believe that more studies employing this method may provide a better understanding of some of the NSCs with distinct patterns of high-order interdependencies. Such future studies will also contribute to understanding the benefits of meditation, hypnosis, and AICT from an information processing perspective.

CRediT authorship contribution statement

Pradeep Kumar G.: Writing – original draft, Writing – review & editing, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Rajanikant Panda:** Writing – review & editing, Writing – original draft, Methodology, Data curation, Conceptualization. **Kanishka Sharma:** Writing – review & editing, Funding acquisition, Conceptualization. **A. Adarsh:** Writing – review & editing, Conceptualization. **Jitka Annen:** Writing – review & editing, Investigation. **Charlotte Martial:** Writing – review & editing, Investigation. **Marie-Elisabeth Faymonville:** Writing – review & editing, Conceptualization, Investigation. **Steven Laureys:** Writing – review & editing, Conceptualization. **Corine Sombrun:** Writing – review & editing, Validation. **Ramakrishnan Angarai Ganesan:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Funding acquisition, Conceptualization. **Audrey Vanhaudenhuyse:** Writing – original draft, Writing – review & editing, Visualization, Validation, Investigation, Funding acquisition, Conceptualization. **Olivia Gosseries:** Writing – original draft, Writing – review & editing, Methodology, Visualization, Validation, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest. C.S. is the founder of TranceScience Research Institute in Paris.

Data availability

The EEG data used in the proposed study were recorded at different research centres as part of different fundings that involved other questionnaires, experiments, and physiological signals such as ECG and respiration, whose analyses are still in progress. Hence, the data used would be made publicly available at a later time according to the rules and regulations of the funding.

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Appendix A. Supplementary data

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