Brain and Cognition 83 (2013) 227–233

Contents lists available at ScienceDirect

Brain and Cognition

journal homepage: www.elsevier.com/locate/b&c

Hypnotic assessment based on the Recurrence Quantification Analysis of EEG recorded in the ordinary state of consciousness

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ARTICLE INFO

Article history:
Accepted 21 August 2013
Available online 19 September 2013

Keywords:
Hypnotic susceptibility
EEG
Recurrence Quantification Analysis
Non-linear time series
Hypnotisability

ABSTRACT

The cerebral cortical correlates of the susceptibility to hypnosis in the ordinary states of consciousness have not been clarified. Aim of the study was to characterize the EEG dynamics of subjects with high (*highs*) and low hypnotisability (*lows*) through the non-linear method of Recurrence Quantification Analysis (RQA). The EEG of 16 males – 8 *highs* and 8 *lows* – was monitored for 1 min without instructions other than keeping the eyes closed, being silent and avoiding movements (short resting), and during 15 min of simple relaxation, that is with the instruction to relax at their best. *Highs* and *lows* were compared on the RQA measures of Determinism (DET) and Entropy (ENT), which are related to the signal determinism and complexity. In the short resting condition discriminant analysis could classify *highs* and *lows* on the basis of DET and ENT values at temporo-parietal sites. Many differences in DET and all differences in ENT disappeared during simple relaxation, although DET still separated the two groups in the earliest 6 min of relaxation at temporo-parietal sites. Our RQA based approach allows to develop computer-based methods of hypnotic assessment using short-lasting, single channel EEG recordings analyzed through standard mathematical methods.

1. Introduction

Hypnotisability is a cognitive multidimensional trait measured by scales (Green, Barabasz, Barrett, & Montgomery, 2005). It is associated with the proneness to accept suggestions (both under hypnosis and in the ordinary state of consciousness), and with a number of physiological and behavioral differences which can be observed also in the absence of specific suggestions (Santarcangelo, 2011; Santarcangelo et al., 2012).

The possible differences in the cortical activity of subjects with high (*highs*) and low hypnotisability scores (*lows*) in resting conditions not preceded by hypnotic induction have not been definitely assessed. Most studies have investigated the cerebral cortical activity through spectral analysis, but they have not provided EEG-based criteria able to classify *highs* and *lows* (De Pascalis, Marucci, & Penna, 1989; De Pascalis, Ray, Tranquillo, & D'Amico, 1998; Graffin, Ray, & Lundy, 1995; Perlini & Spanos, 1991; Sabourin, Cutcomb, Crawford, & Pribram, 1990; Sebastiani, Simoni, Gemignani, Ghelarducci, & Santarcangelo, 2005; Williams & Gruzelier, 2001). Studies based on techniques from nonlinear dynamics views (Baghdadi & Nasrabadi, 2009; Lee et al., 2007) and on the combination of linear and nonlinear methods, such as empirical mode decomposition, mean phase coherence and weighted frequency, signal energy, fractal dimension, scaling exponent (Baghdadi & Nasrabadi, 2012) have shown significant relation between hypnotisability and features extracted from EEG signals only after hypnotic induction.

In the framework of nonlinear methods, the Recurrence Quantification Analysis (RQA) is a suitable tool to characterize the dynamics of nonlinear systems (Facchini, Mocenni, Marwan, Vicino, & Tiezzi, 2007; Marwan, Romano, Thiel, & Kurths, 2007; Mocenni, Facchini, & Vicino, 2010) through the Recurrence Plot, which provides a pictorial representation of recurrences in complex time series. The concept of recurrence is closely related to that of dynamical system, as demonstrated by Poincaré, who stated that "certain systems will, after a sufficiently long time, return to a state very close to the initial state". Indeed, repeating patterns are found in all dynamical systems and the degree of recurrences contains most of the relevant information about the systems behavior. The Recurrence Plot is built by using a reconstructed dynamical system (Takens, 1981) and is analyzed by RQA measures able to automatically extract and quantify recurrences. RQA measures have been used to characterize EEG signals because their evaluation does not require any assumption on stationarity,

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http://dx.doi.org/10.1016/j.bandc.2013.08.002

length or noise of time series (Schinkel, Marwan, & Kurths, 2009; Webber & Zbilut, 1994). For example, RQA applied to EEG has revealed sleep stages (Song, Lee, & Kim, 2005), conditions of consciousness/unconsciousness (Becker et al., 2010) and pre-ictal activity in epileptic subjects (Thomasson, Hoeppner, Webber, & Zbilut, 2001).

Among the RQA variables characterizing the dynamics of signals, Determinism and Entropy relate to the signals determinism and complexity (Supplementary Electronic Material) and have been proven to be suitable indicators for discriminating between different dynamical regimes in very complex signals (Mocenni et al., 2010). Thus, the aim of the present study was to assess whether, in the ordinary state of consciousness, *highs* and *lows* differ in the Determinism and Entropy extracted by RQA from EEG signals during both a very short resting condition not associated with any instruction (short resting) and/or during a longer one associated only with the instruction to relax (simple relaxation) (Benson, Arns, & Hoffman, 1981). Indeed, trait differences may be present independently of any instruction and/or emerge/disappear in the completion of the relaxation task, as previously observed through the EEG spectral analysis (Sebastiani et al., 2005).

2. Methods

2.1. Subjects

After the approval of the Ethics Committee of the University of Pisa, participants were selected among the students attending Physiology classes after their written informed consent. The experimental paradigm followed the rules of the Declaration of Helsinki. Hypnotic assessment was performed according to the Italian version of the Stanford Hypnotic Susceptibility Scale, form C (De Pascalis, Bellusci, & Russo, 2000) in 121 males. The sample consisted of 10 *highs*, 77 medium hypnotisables and 34 *lows*. Eight *highs* (SHSS score (mean ± SD): 10 ± 0.9) volunteered for the present study and the same number of subjects was recruited by chance in the *lows'* group (score 1.5 ± 0.4). They were informed that no hypnotic induction will be administered in the experimental session for EEG recording, which was scheduled at least two months after hypnotic assessment. Participants were matched for age (*highs*: 20.6 ± 0.8; *lows*: 21.4 ± 1.0) and education (Italian nationality, scientific education, non-agonistic sports, no artistic hobby such as music, dance, painting). They were naïve to relaxation techniques, with the exception of the experience of hypnotic assessment.

2.2. Experimental procedure

EEG was recorded between 2.00 and 4.00 p.m., at least 3 h after the latest meal and coffee beverage in a semi-darkened, sound attenuated and temperature controlled room (22°). Participants were sitting in a semi-reclined position and asked to keep their eyes closed and to avoid movements and speaking. EEG was monitored for 1 min without any further instructions (short resting). Then, subjects were invited to score their present subjective relaxation (range 0–10). Immediately afterwards, they were asked to relax "at their best", which is the instruction used to induce a "simple relaxation" condition, characterized by the occurrence of a relaxation response (Benson et al., 1981). EEG was monitored for 15 min which were divided in 5 intervals lasting 3 min each ($I_1, \ldots I_5$) a posteriori. At the end of the session, participants were again asked to score their subjective relaxation (range 0–10). No subject reported to have used specific relaxation procedures such as breathing or eye movements.

2.3. Signal acquisition and preprocessing

Standard electroencephalographic recordings (32-channels for EEG, 8-ch for auxiliary signals; sampling rate:1000 Hz; band-pass filter: 0.1–100 Hz) were performed according to the International 10–20 System by Ag/AgCl electrodes embedded in an elastic cap (Quick-Caps from Compumedics/Neuroscan). Scalp EEG signals grounded at FPz were referenced to the FCz potential; then, the records were re-referenced off-line to a linked ear-lobes reference. Two horizontal (outer left and right canthus) and two vertical electro-oculogram (EOG) electrodes (above and below the right eye) recorded bipolarly eye movements and blinks. Electrode impedance was kept below 5 kΩ. After visual inspection for the elimination of large artifacts, less than 10% of the short resting period and of each interval of the relaxation session was removed. A band-pass digital filter (0.5, 100 Hz) was applied to EEG signals to remove DC bias and non-significant high frequencies contributions; a notch filter was used to reduce the 50 Hz power-line noise. The FASTER algorithm (Nolan, Whelan, & Reilly, 2010) was used to remove the ECG and EOG contaminations. It is based on the well-known independent component analysis (ICA) and performs the removal of undesired components by comparing the autocorrelation of the ECG and EOG signals to the corresponding independent components.

2.4. Recurrence Quantification Analysis

Among the several indicators provided by RQA, only Determinism and Entropy have been considered in this study, according to recent studies showing that they are sufficient to describe significant changes in the systems dynamics, especially for classification purposes (Mocenni et al., 2010). The calculation of these recurrence quantification indicators is performed in order to obtain information on the dynamical properties of the reconstructed trajectory of the system in the phase space. In particular, after defining the embedded state space by the method of delayed coordinates, the RP for each electrode and each subject has been constructed and the recurrence indicators Determinism and Entropy have been quantified. Determinism (DET) evaluates the proportion of recurrent points forming diagonal line structures in the RP and relates to the time series predictability; Entropy (ENT) reflects the information content of the RP structure, thus representing the complexity of the signal (Webber & Zbilut, 2005). In this study, the state space (Supplementary Electronic Material) has been reconstructed by using estimated space dimension $D_E = 3$ and time lag $\tau = 1200$ (samples) (Becker et al., 2010). The RP was constructed by setting the threshold $\epsilon = 15$ (Thomasson et al., 2001) and Theiler window $w = 10$.

2.5. Statistical analysis

The SPSS.15 package was used for the analysis of Determinism and Entropy. Data from C3 were not included because 4 subjects exhibited poor EEG signals due to unstable cap connections. Hypnotisability was the *between* subject factor in all analyses. Multivariate ANOVA was applied to the DET and ENT values of the short resting condition and of each interval of simple relaxation (I_1–I_5). Side effects were not investigated owing to the large number of factors with respect to the number of subjects. Repeated measures ANOVA was applied to DET and ENT collapsed sites of the relaxation session with interval as *within* subjects factor to study possible changes across time. Stepwise discriminant analysis was then applied to the sites indicated by MANOVA as significantly different between *highs* and *lows*. Pearson correlation coefficients were computed between the values of DET/ENT in the short lasting