ELSEVIER

Neuroscience Letters 330 (2002) 143–146

Neuroscience Letters

www.elsevier.com/locate/neulet

Non-linear dynamic complexity of the human EEG during meditation

L.I. Aftanas*, S.A. Golocheikine

Psychophysiology Laboratory, State-Research Institute of Physiology, Siberian Branch, Russian Academy of Medical Sciences, Timakova str. 4, 630117, Novosibirsk, Russia

Received 28 May 2002; received in revised form 1 July 2002; accepted 2 July 2002

Abstract

We used non-linear analysis to investigate the dynamical properties underlying the EEG in the model of Sahaja Yoga meditation. Non-linear dimensional complexity (DCx) estimates, indicating complexity of neuronal computations, were analyzed in 20 experienced meditators during rest and meditation using 62-channel EEG. When compared to rest, the meditation was accompanied by a focused decrease of DCx estimates over midline frontal and central regions. By contrast, additionally computed linear measures exhibited the opposite direction of changes: power in the theta-1 (4–6 Hz), theta-2 (6–8 Hz) and alpha-1 (8–10 Hz) frequency bands was increased over these regions. The DCx estimates negatively correlated with theta-2 and alpha-1 and positively with beta-3 (22–30 Hz) band power. It is suggested that meditative experience, characterized by less complex dynamics of the EEG, involves 'switching off' irrelevant networks for the maintenance of focused internalized attention and inhibition of inappropriate information. Overall, the results point to the idea that dynamically changing inner experience during meditation is better indexed by a combination of non-linear and linear EEG variables. © 2002 Elsevier Science Ireland Ltd. All rights reserved.

Keywords: EEG; Dimensional complexity; Non-linear dynamics; EEG band power; Meditation

The application of non-linear system theory to the EEG has been shown to offer new ways of analyzing neural regulation at a gross (mass action) level [4,12,20]. According to Hebb's view of neuron assemblies as functional processing units, in the working brain there may be not only one or two, but a much larger number of cell assemblies oscillating synchronously at different frequencies. In this case the number of cell assemblies activated can be considered as an indicator of complexity of neuronal computations in the brain [4,8]. The geometrical measure, EEG dimensional complexity (DCx), derived from non-linear system theory, has been often calculated in order to elucidate the key aspects of brain dynamics such as overall complexity [4,12]. The dimension calculated from EEG time series has been shown to be a monotonically increasing function of the number of independent neural processes [8]. This implies that the calculated dimension value in different tasks can, in principle, be related to the number of neural assemblies active simultaneously in the brain [8,12].

DCx estimates have also been used as evidence of non-linearity and possible nonlinear determinism (deterministic chaos of the strange-attractor type) of EEG signal mostly without any proof (for review see Ref. [4]). However, special works have shown that the values of this measure in linearly-correlated noise are very similar to those obtained from a system clearly chaotic in nature [15]. Results of subsequent investigations with surrogate data tests indicated that EEG was not produced by low-dimensional chaos; however, it was non-linear (for a short review see Refs. [12,13]). Nonetheless, estimated EEG DCx provides a valuable relative, generic measure of the dynamical complexity of a time series regardless of the source of the complexity (chaos, linear and nonlinear stochasticity) [2,4,7,9,10,16,17]. Thus, the issues of non-linearity in general and low-dimensional chaos in particular are separate from the issue of utility of estimated DCx as an EEG measure [13] (p. 487). Of special note are variations in scalp distribution of DCx estimates of discriminating perception and imagery processes [7,17], different attentional [9] and emotional [2] states, and creative and convergent thinking modes [10].

The present study was undertaken to examine how dyna-

* Corresponding author. Tel.: +7-3832-334387; fax: +7-3832-324254.

E-mail address: aftanas@iph.ma.nsc.ru (L.I. Aftanas).

PII: S0304-3940(02)00745-0

mically changing inner experience during meditation is indexed by EEG DCx estimates. Findings from our earlier investigation show that meditation was accompanied by theta and alpha synchronization as well as enhanced theta long-distance connectivity [1]. Considering the existence of inverse correlational relationships between DCx estimates and EEG power mainly in lower frequency bands [19,20], the prediction was that meditation would be accompanied by less complex dynamics.

This study is essentially a reanalysis of the data from our previous EEG investigation of Sahaja Yoga meditation [1], which is a model of conscious mental process, characterized by internalized attention and emerging emotionally positive experiences. The key experience during Sahaja Yoga meditation is a state called ‘thoughtless awareness’ or ‘mental silence’ in which the meditator is alert and aware but is free of any unnecessary mental activity. The state of ‘thoughtless awareness’ is usually accompanied by emotionally positive experience of ‘bliss’. In general, the outcome of the meditative process is associated with a sense of relaxation and positive mood and a feeling of benevolence towards oneself and others [14]. The EEG was recorded during the eyes closed rest and meditation condition. Scan 4.1.1 software, a 128-channel ESI System (ESI-128, NeuroScan Labs.) and 64-channel QuikCap with imbedded Ag/AgCl electrodes (NeuroSoft, Inc.) were used to record EEG from 62 active scalp sites referenced to the tip of the nose along with both vertical and horizontal EOGs. Three artifact free EEG segments by 8.192 s (i.e. 4096 points) were selected for each condition (for details see Ref. [1]). In contrast to previous investigations, some modifications were performed: (1) since reliable effects of meditation on the EEG activity were obtained only in experienced meditators, short-term meditators were not included in the analysis; (2) four recently recorded experienced meditators were included for analyses so the total sample of subjects reached 20 right-handed subjects (males, $n = 9$; females, $n = 11$) between the ages of 20 and 40 years who were regularly practicing meditation.

For the present study, the EEG segments were preliminary bandpass filtered (4–30 Hz) by means of an acausal filter and subjected to non-linear analysis. Using the licensed algorithm [18] we calculated the mean PD2i estimate, based on the averaged serial PD2i slopes found for the 9th through 12th embeddings (M) with the associated standard deviations (for details see Refs. [2,18]). For linear analyses the same EEG segments were epoched into two 4096 ms (i.e. 2048 points) epochs, fast Fourier transformed (FFT) and averaged in the frequency domain using a Parzens window. The FFTs were then grouped into the theta-1 (4–6 Hz), theta-2 (6–8 Hz), alpha-1 (8–10 Hz), alpha-2 (10–12 Hz), beta-1 (12–18 Hz), beta-2 (18–22 Hz) and beta-3 (22–30 Hz) frequency bands, log-transformed, and averaged across three EEG traces.

Lateral electrodes were collapsed into eight electrode clusters. This procedure resulted in four regional means for each hemisphere: anterio-frontal (AF), fronto-central (FC), centro-parietal (CP) and parieto-occipital (PO). Electrodes of the midline were also collapsed into four electrode clusters: anterio-frontal (mAF - AFz, Fz), fronto-central (mFC - FCz, Cz), centro-parietal (mCP - CPz, Pz), and parieto-occipital (mPO - POz, Oz) zones (Fig. 1). Power values and DCx estimates over individual electrodes were averaged to form regional means. DCx estimates for symmetrical cortical regions were subjected to four-way repeated measures ANOVAs, involving factors of Condition (COND: rest, meditation), Hemisphere (HEM: left, right), Caudality (CAUD: anterior, posterior) and Localization (LOC: 2). For midline regions three-way ANOVAs (COND (2) $\times$ CAUD (2) $\times$ LOC (2)) were applied. All analyses were followed by post-hoc comparisons (Scheffe test). Degrees of freedom were Greenhouse–Geisser corrected where appropriate.

ANOVAs of DCx estimates for symmetrical regions revealed no effects of meditation. By contrast, ANOVAs for midline regions resulted in significant COND $\times$ CAUD interactions ($F(1, 19) = 8.60$, $P < 0.009$). Inspection of respective means of this interaction (Fig. 2) points to decreased DCx during the meditation condition over midline anterior cortical regions.

Since effects of meditation were associated with midline regions, only spectral power values from these regions were subjected to repeated measures ANOVAs. Among seven frequency bands theta-1, theta-2, alpha-1 and alpha-2 bands revealed effects associated with the meditation condition (Fig. 3). According to a significant COND $\times$ CAUD interaction ($F(1, 19) = 9.44$, $P < 0.006$) for the theta-1

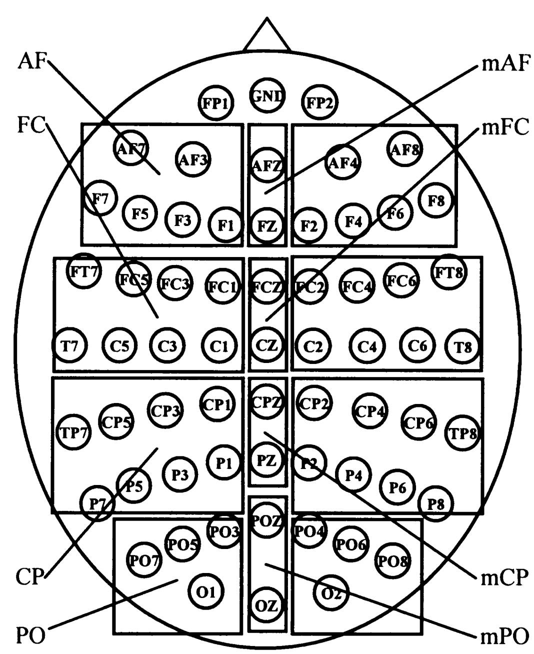

Fig. 1. The electrocap layout and 12 electrode clusters (eight lateral: AF, FC, CP, and PO for the left and right hemispheres; four midline: mAF, mFC, mCP, and mPO).

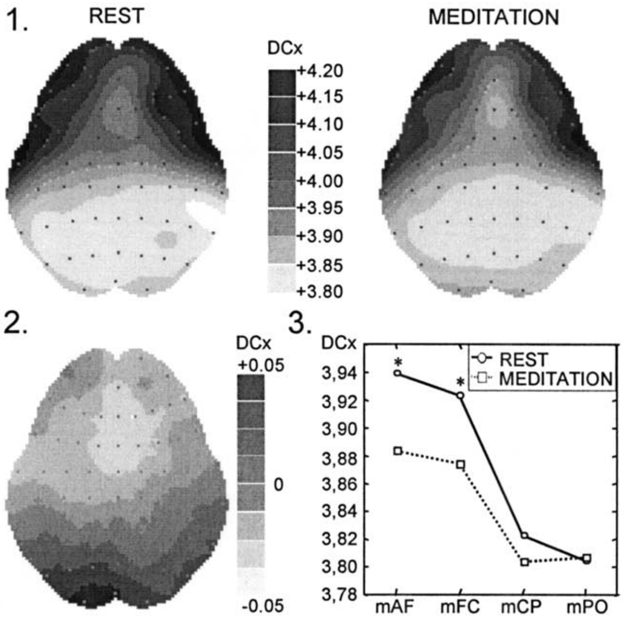

Fig. 2. (1) Maps representing the topographical distribution of the mean values of EEG DCx estimates for the eyes closed and meditation conditions. (2) Map of differences between rest and meditation conditions. (3) Mean values of EEG DCx estimates over the midline cortical regions for the eyes closed and meditation conditions. $*P < 0.05$ (post-hoc comparisons, Scheffe test).

band, meditation was accompanied by a power increase over anterior midline regions. The significant effect of the factor of COND ($F(1, 19) = 6.26$, $P < 0.022$) for the theta-2 band points to the overall increase of power during meditation, which, however, was slightly more pronounced over anterior regions. As indexed by the interaction COND × CAUD ($F(1, 19) = 5.40$, $P < 0.031$) for the alpha-1 band, meditative experience yielded a power increase over anterior midline regions. Finally, as evidenced by the interaction COND × CAUD × LOC ($F(1, 19) = 4.55$, $P < 0.046$), in the alpha-2 band meditation induced focused power increase over the posterio-occipital (mPO) region.

Correlational analyses of DCx estimates and spectral power values from anterior midline regions revealed significant relationships among them during the meditation condition: DCx estimates negatively correlate with theta-2 (range from $r = -0.52$ to $r = -0.57$) and alpha-1 (range from $r = -0.56$ to $r = -0.66$), and positively with beta-3 (range from $r = -0.55$ to $r = -0.59$) band power.

Summarizing, the effects of meditation were differentially reflected by local EEG DCx, theta and lower alpha band power changes.

As mentioned above, in this paper changes in DCx are considered as changes in the complexity of neuronal computations. During the meditation condition significant changes of dynamical complexity were manifested as a focused decrease of EEG DCx estimates over midline anterio-frontal and centro-frontal regions. There are several findings indicating that DCx of the EEG from frontocortical regions is negatively correlated with attentional control (effort) over cognitive processing. Increased attentional control [9] was accompanied by decreased DCx, whereas different normal and pathological brain states of loosened attention such as imagery [7,17], divergent thinking mode [10] or schizophrenia [16] were associated with increased DCx over fronto-cortical regions. The finding of lower DCx over midline frontal areas during meditation suggests that controlled allocation of attentional resources was required for the maintenance of the target meditative state and the inhibition of inappropriate stimuli. The reduction of the dimensionality might be an expression of strongly coupled oscillators or the inactivation of previously active networks [8]. It is quite possible that this effect is influenced by activities of the cingulum, which is involved in the meditation process [11]. One may assume that meditative experience accompanied by decreased DCx involves 'switching off' irrelevant networks for the maintenance of focused internalized attention and inhibition of inappropriate information. To some extent, the obtained findings fit the preliminary statement by Elbert et al. [4], according to which "…the task performance increases dynamical complexity over those brain areas with little involvement in the task, but reduces the DCx in those areas in which networks became actively engaged" (p. 35).

As for the linear measures, the revealed theta-2 power increase over anterior midline electrodes may reflect recruitment of theta oscillating networks in focused attention mechanisms [1,3,5,6] associated with meditative process. A possible interpretation of lower alpha power changes

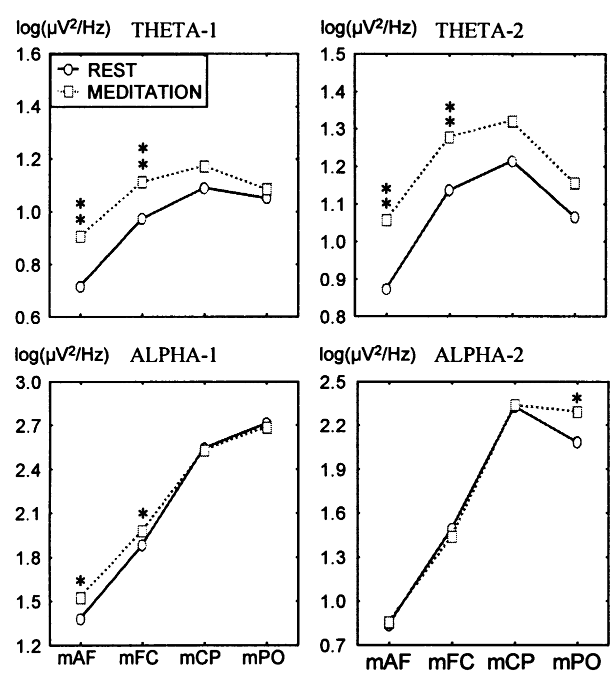

Fig. 3. Mean values of theta-1, theta-2, alpha-1, and alpha-2 EEG band power over the midline cortical regions for the eyes closed rest and meditation conditions. $*P < 0.05$; $**P < 0.01$ (post-hoc comparisons, Scheffe test).

during meditation may be ascribed to functional heterogeneity of different alpha frequency bands. According to a variety of experimental paradigms, desynchronization in the lower alpha band reflects processes of external attention such as alertness/vigilance (e.g. Ref. [6]). One may assume that meditative experience is mediated by 'switching off' mechanisms of external attention as indexed by enhanced alpha-1 synchronization over anterior cortical regions. It is very indicative that inverse correlations of DCx estimates with theta and lower alpha band power, seen in cognitive experimental paradigms [19], were selectively obtained for cortical regions involved in the meditative process. Finally, high band power, which did not yield significant changes during the meditation condition vs. rest, did reveal significant positive correlations with DCx estimates. The nature of these correlations, indicating that lower complexity is accompanied by lower beta-3 power values during meditation, needs further clarification.

Overall, the results point to the idea that dynamically changing inner experience during meditation are better indexed by a combination of linear and non-linear EEG variables, giving additional insight into the integrative functioning of the CNS with respect to altered states of consciousness.

[1] Aftanas, L.I. and Golocheikine, S.A., Human anterior and frontal midline theta and lower alpha reflect emotionally positive states and internalized attention: high-resolution EEG investigation of meditation, Neurosci. Lett., 310 (2001) 57–60.

[2] Aftanas, L.I., Lotova, N.V., Koshkarov, V.I., Makhnev, V.P. and Popov, S.A., Non-linear dynamic complexity of the human EEG during evoked emotions, Int. J. Psychophysiol., 28 (1998) 63–67.

[3] Basar, E., Schurmann, M. and Sakowitz, O., The selectively distributed theta system: functions, Int. J. Psychophysiol., 39 (2001) 197–212.

[4] Elbert, T., Ray, W.J., Kowalik, Z.J., Skinner, J.E., Graf, K.E. and Birbaumer, N., Chaos and physiology: deterministic chaos in excitable cell assemblies, Physiol. Rev., 74 (1994) 1–47.

[5] Inanaga, K., Frontal midline theta rhythm and mental activity, Psychiatr. Clin. Neurosci., 52 (1998) 555–566.

[6] Klimesch, W., EEG alpha and theta oscillations reflect cognitive and memory performance: a review and analysis, Brain Res. Brain Res. Rev., 29 (1999) 169–195.

[7] Lutzenberger, W., Elbert, T., Birbaumer, N., Ray, W.J. and Schupp, H., The scalp distribution of the fractal dimension of the EEG and its variation with mental tasks, Brain Topogr., 5 (1992) 27–34.

[8] Lutzenberger, W., Preissl, H. and Pulvermuller, F., Fractal dimension of electroencephalographic time series and underlying brain processes, Biol. Cybern., 73 (1995) 477–482.

[9] Molle, M., Marshall, L., Pietrowsky, R., Lutzenberger, W., Fehm, H.L. and Born, J., Dimensional complexity of EEG indicates a right fronto-cortical locus of attentional control, J. Psychophysiol., 9 (1995) 45–55.

[10] Molle, M., Marshall, L., Wolf, B., Fehm, H.L. and Born, J., EEG complexity and performance measures of creative thinking, Psychophysiology, 36 (1) (1999) 95–104.

[11] Newberg, A., Alavi, A., Baime, M., Pourdehnad, M., Santanns, J. and Aquilli, E., The measurement of regional cerebral blood flow during the complex cognitive task of meditation: a preliminary SPECT study, Psychiatry Res.: Neuroimag. Section, 106 (2001) 113–122.

[12] Pritchard, W.S. and Duke, D.W., Measuring "chaos" in the brain: a tutorial review of EEG dimension estimation, Brain Cogn., 27 (1995) 353–397.

[13] Pritchard, W.S., Duke, D.W. and Krieble, K.K., Dimensional analysis of resting human EEG II: surrogate-data testing indicates nonlinearity but not low-dimensional chaos, Psychophysiology, 32 (1995) 486–491.

[14] Rai, U.C., Medical Science Enlightened, Life Eternal Trust, London/New York, 1993.

[15] Rapp, P.E., Albano, A.M., Schmah, A.M. and Farwell, L.A., Filtered noise can mimic low-dimensional chaotic attractors, Phys. Rev. E, 47 (1993) 2289–2297.

[16] Saito, N., Kuginuki, T., Yagyu, T., Kinoshita, T., Koenig, T., Pascual-Marqui, R.D., Kochi, K., Wackermann, J. and Lehmann, D., Global, regional, and local measures of complexity of multichannel electroencephalography in acute, neuroleptic-naive, first-break schizophrenics, Biol. Psychiatry, 43 (11) (1998) 794–802.

[17] Schupp, H.T., Lutzenberger, W., Birbaumer, N., Miltner, W. and Braun, C., Neurophysiological differences between perception and imagery, Cogn. Brain Res., 2 (1994) 77–86.

[18] Skinner, J.E., Molnar, M. and Tomberg, C., The point correlation dimension: performance with non-stationary surrogate data and noise, Integr. Physiol. Behav. Sci., 29 (1994) 217–234.

[19] Stam, C.J., Brain dynamics in theta and alpha frequency bands and working memory performance in humans, Neurosci. Lett., 286 (2) (2000) 115–118.

[20] Tirsch, W.S., Keidel, M., Perz, S., Scherb, H. and Sommer, G., Inverse covariation of spectral density and correlation dimension in cyclic EEG dynamics of the human brain, Biol. Cybern., 82 (1) (2000) 1–14.