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Non-linear analysis of emotion EEG: calculation of Kolmogorov entropy and the principal Lyapunov exponent

Ljubomir I. Aftanas[a,*], Natalia V. Lotova[a], Vladimir I. Koshkarov[a], Vera L. Pokrovskaja[a], Serguei A. Popov[a,b], Victor P. Makhnev[a]

[a]*Psychophysiology Laboratory, Institute of Physiology, Siberian Branch Russian Academy of Medical Sciences, Timakova strasse 4, 630117 Novosibirsk, Russia*

[b]*Laboratory of Digital Methods of Image Processing, Institute of Automation and Electrometry, Siberian Branch Russian Academy of Sciences, Universitetsky prosp., 1, 630090, Novosibirsk, Russia*

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Abstract

For 76 healthy subjects, two non-linear measures, capturing the dynamical properties of the system orbiting within the attractor (i.e. Kolmogorov entropy, K2 and principal Lyapunov exponent, L1), were calculated from EEG segments, corresponding to different states of brain activity, induced by emotionally valenced (i.e. neutral, affective positive and negative) video stimuli. Significantly elevated values of EEG K2 and L1 in response to both positive and negative film categories as compared to neutral one were evidenced. Relying on the obtained findings, it is suggested that increased cortical dynamics, up to a certain level, are probably necessary for emotion functioning. © 1997 Elsevier Science Ireland Ltd.

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The application of non-linear system theory to the EEG has been shown to offer information beyond that provided by traditional EEG measures [3,8,9,12,14], thus offering new ways of analyzing neural regulation at a gross (mass action) level [8,12]. To date, essentially three different types of measures have been employed to characterize attractors in physiological systems. First, measures of dimension focus on the system's geometric (static) structure. This is the measure, that, when applied to EEG data, is conventionally termed EEG dimensional complexity (DCx). It provides an index of the global complexity's degree of EEG dynamics reconstructed in state space by the methods of delays (for review see [8]). The second type, that of entropy and information, and the third type, the spectrum of Lyapunov exponents, capture the dynamical properties of the system orbiting within the attractor [8,9,15–17]. More particularly, the Kolmogorov entropy metric evaluates the degree of 'chaoticness' of the system, or the average rate at which information is generated by the system, or, equivalently, the rate at which current information about system is lost [8,17]. In turn, Lyapunov exponents provide an estimate of the mean exponential divergence or convergence of nearby trajectories in phase space, expressing the sensitive dependence on initial conditions. The calculation of a clearly positive principal Lyapunov exponent provide evidence that system under investigation is chaotic [8,9,15,16].

Up to now, affective cortical activation and effects of different emotions have received little attention in non-linear EEG studies. Higher dimensional complexity of EEG activity over frontal cortical regions was found during emotional imagery than during mental arithmetic tasks [5,14]. Our researches have shown that EEG DCx may characterize rather specific aspects of emotional experiences [2,4] as well as personality differences in affective reactivity [3].

Considering that non-linear system's geometric (i.e. EEG DCx) measure is totally different from both dynamical K2 and L1 EEG measures, the goal of this study was the further elucidation of the basic non-linear processes, underlying cortical mechanisms of emotion functioning. We addressed

* Corresponding author. Tel.: +7 383 2 324255; fax: +7 383 2 324254; email: aftanas@pslphys.nsk.su

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two principal questions: (1) Would ‘neutral’ and ‘affective’ multichannel EEG be discriminated on the basis of non-linear dynamical measures, that of Kolmogorov entropy and Lyapunov exponent? (2) Would these two non-linear measures succeed in a more specific discrimination, namely, between positive and negative affective valences?

Subjects (Ss; $n = 76$) were right-handed college students between the ages of 17 and 20 years. The experiment began with the 90-s staring baseline and warming-up clip. After this, three video clip sessions (neutral, positive, and negative, respectively) were presented. All the clips were balanced by cuts and script elements and produced significant ‘linear’ EEG effects of frontocortical alpha asymmetries in valence discrimination [1,4], well documented in the literature [6,7]. Each clip trial consisted of: (1) a brief count-down; (2) the clip presentation; (3) a 1-min post film rest period; and (4) subjective ratings, which assessed subject’s emotional reactions during the preceding film. For each S and each film category, average ratings for discrete positive (happiness, amusement, satisfaction) and negative (sadness, disgust, and anxiety) emotions were expressed in composite rating indexes of the global positive and negative affect (GPA and GNA, respectively) [4,7].

EEG was recorded from 16 derivations (F7, F8, F3, F4, Fz, C3, C4, Cz, T5, T6, P3, P4, Pz, O1, O2, and Oz), referred to linked earlobes. The vertical and horizontal EOGs were measured to control for ocular artifacts. The EEG and EOG signals were amplified by a multichannel biosignal amplifier (bandpass 0.08–30 Hz, –6 dB/octave) and A/D converted at 250 samples/s per channel with 12-bit resolution. As a result, for each S and each film category (i.e. NEUT, POS, and NEG) three artifact-free and EOG corrected [10] EEG epochs of 8.192 s (i.e. 2048 points) were selected. The initial band-pass of all selected EEG epochs was reduced by means of acausal FFT filter with a digital bandpass of 0.8–28 Hz (3 dB points; 18 dB down at 0.3 and 29.0 Hz). The Grassberger and Procaccia algorithm was used for the reconstruction of attractor by the methods of delays [11]. The order two Kolmogorov entropy (K2) of an attractor was calculated using the maximum-likelihood estimation method [17]. For calculating the largest Lyapunov exponent (L1), the Rosenstein et al.’s method was used [16]. For both K2 and L1 metrics the time delay was set at $\tau = 3$ and the embedding dimension at $d = 12$. The units of K2 and L1 were expressed in nats/s. In addition, following Fast Fourier transformation average ln power values were calculated for the alpha (7.5–12.5 Hz) frequency band, indicative for both arousal changes and regional EEG specialization for emotions [6,7].

For intensity self-report values, a two-way Condition (COND: PRE, NEUT, POS, NEG, and POST) $\times$ Affect (AFF: GPA, GNA) repeated measures ANOVAs were computed and the highly significant main effect of COND ($F(4,296) = 20.92$, $P < 0.0001$) and AFF ($F(1,74) = 122.92$, $P < 0.0001$) as well as COND $\times$ AFF interaction ($F(4,296) = 157.38$, $P < 0.0001$) were evidenced (Fig. 1). Post-hoc Scheffe tests indicated that in comparison to PRE, NEUT and POST condition, GPA and GNA values in response to positive and negative film category were significantly more intense, all Ps < 0.0001 (Fig. 1). Thus we concluded that positive and negative emotions were successfully induced.

For the values of ln alpha, K2 and L1, separate two-way Valence (VAL: NEUT, POS, and NEG) $\times$ Localization (LOC: 16) repeated measures ANOVAs were computed. As the lowest level of analyses, a one-way VAL (3: NEUT, POS, NEG) ANOVAs for a single locus were used to specify significant VAL $\times$ LOC interaction terms. All post-hoc comparisons were computed with the Scheffe test. Greenhouse-Geisser corrected P-values were employed where appropriate.

The statistically robust main effect of the VAL factor ($F(2,150) = 26.53$, $P < 0.0001$) indicated lower alpha power values for both positive (5.03) and negative (4.96) film categories as compared to the neutral (5.21) one overall (both comparisons at $P < 0.0001$ in post-hoc tests; Fig. 2). There was also highly significant effect of LOC ($F(15,1125) = 265.06$, $P < 0.0001$), as well as VAL $\times$ LOC interaction ($F(30,2250) = 17.76$, $P < 0.0001$). Alpha power values were higher in neutral as compared to negative affective stimulation over all cerebral loci except F7 and F3 electrodes (the lowest $P < 0.0327$). In case of neutral versus positive affective stimulation comparisons, the picture was nearly the same: for all but F3 and C3 cerebral sites, there were also significantly higher power values in case of neutral stimulation (the lowest $P < 0.0144$). Finally, the locally lower power values for positive then negative stimulation at F7 locus ($P < 0.0299$) were accompanied by significantly higher power values for positive then negative video clips at C4, P4, T6, O1, Oz, O2 loci (the lowest $P < 0.0460$, Fig. 2).

For the EEG K2 values, the significant main effect of VAL ($F(2,150) = 10.86$, $P < 0.0001$) and LOC ($F(15,1125) = 43.67$, $P < 0.0001$) as well as VAL $\times$ LOC

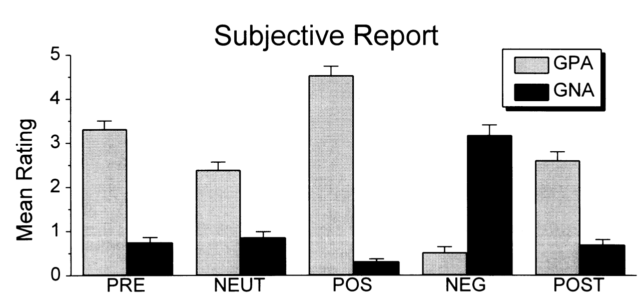

Fig. 1. Mean (± SE) intensity ratings on a series of unipolar scales for global negative and positive affect (GNA and GPA, respectively) throughout the experiment. Note 1, NEUT, POS, and NEG, ratings in response to the neutral, positive and negative affective video stimulation respectively; PRE, ratings before the video stimulation; POST, subjective ratings 4 min after the presentation of the last (i.e. NEG) video clip. Note 2, Positive and negative affective sessions always followed the neutral one, and the two negative clips always followed the two positive clips (for rationale of this see [7]).

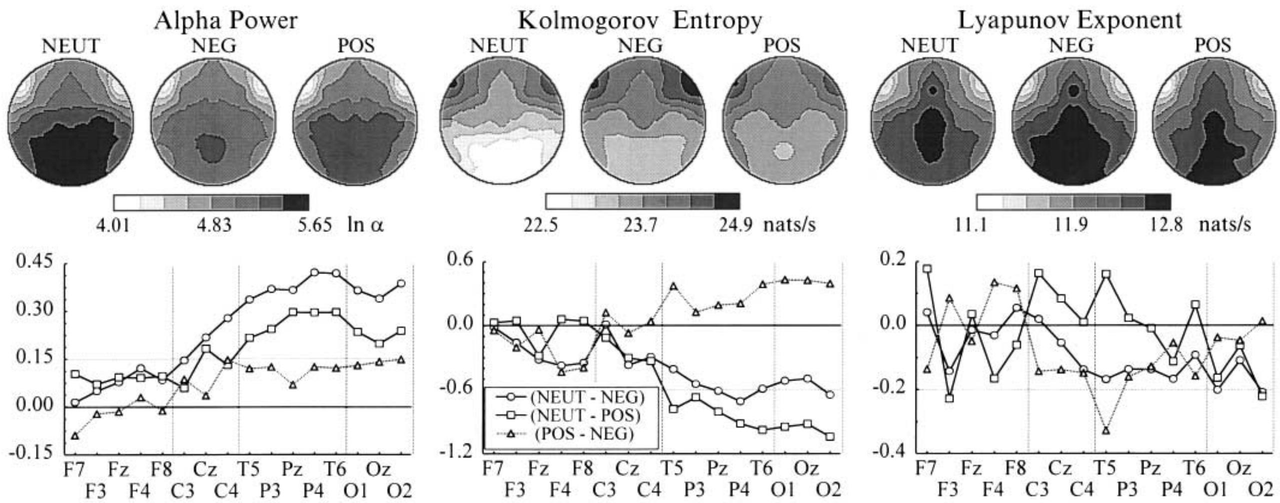

Fig. 2. Map series (upper row), representing the topographical distribution of the mean values for ln alpha power, Kolmogorov entropy (K2) and principal Lyapunov exponent (L1) in response to the neutral (NEUT), negative (NEG), and positive (POS) film category. Lower row represents mean differences (for each electrode) among the film categories.

interaction ($F(30,2250) = 4.27$, $P < 0.0001$) were evidenced. The both positive ($F(1,75) = 19.36$, $P < 0.0001$) and negative ($F(1,75) = 9.56$, $P < 0.0028$) film categories produced significantly higher levels of EEG K2 (23.75 and 23.65, respectively) than neutral stimulation (23.26) overall (Fig. 2). At the level of topography, affective negative condition as compared to neutral one yielded significantly more pronounced increase of K2 levels at P3, Pz, P4, T6, O1, Oz, and O2 loci (the lowest $P < 0.0434$.). In turn, affective positive film category as contrasted with the neutral one, also involved the increase of K2 values with the same topographical picture and additionally at T5 site (all Ps < 0.0001). There were no significant differences for specific positive versus negative affective valence comparisons.

For the L1 values, only significant effect of LOC ($F(15,1125) = 119.44$, $P < 0.0001$) as well as VAL × LOC interaction ($F(30,2250) = 2.56$, $P < 0.0001$) were evidenced. Negative versus neutral film category yielded significantly more pronounced increase of L1 values at O1 ($P < 0.0335$) and O2 ($P < 0.0311$) loci only (Fig. 2). In the neutral versus positive film category comparisons, more elevated L1 values at F3 ($P < 0.0271$) and O2 ($P < 0.0144$) for the positive stimulation was observed. In specific positive versus negative discrimination, the topographical differences were restricted to the left posterior temporal site (T5), evidencing significantly higher levels of L1 values for the negative film category ($P < 0.0001$). Thus, this discrimination must be regarded as relative, since at T5 site neither of the two affective film categories did not differ from the neutral one (all Ps > 0.05).

An important concept in non-linear theory is that of control parameters [8,18]. These are variables related to general properties of the system, such as synaptic efficacy, input-output transfer function of the neuron, the balance between excitation and inhibition etc. Smooth changes in a control parameter can result in a relatively sudden qualitative and quantitative changes in the dynamics of the system. Such changes are called bifurcations. It was suggested that the activity level of non-specific (thalamic and reticular) projections of the cortex could also be a control parameter of cortical dynamics [18]. Increased activity of these projections (i.e. desynchronization), could then result in (a series) of bifurcations, leading to a different, more complex dynamics of cortical networks ([18] p. 222).

Spectral band analysis evidenced the robust alpha desynchronization in response to both affective film categories. In contrast, affective induction significantly increased EEG K2 and L1 values. Presumably, emotional arousal, through a series of putative bifurcations, shift brain activity towards more complex dynamics in terms of EEG DCx [2,4] or greater 'chaoticness' and lesser predictability in view of K2's logic [8,17]. In turn, the building up findings on principal Lyapunov exponent and EEG indicate that changes in L1 values are associated with sleep stages [9,15] and pathological processes [15]. While on the subject of the information processing, a pioneering Lutzenberger et al.'s [13] results evidenced elevated L1 values during mental imagery as compared to the perception condition. Since principal Lyapunov exponents describe the divergence of trajectories starting at nearby initial states, it was suggested [9,15,16] that enhanced L1 values reflect the increased flexibility of information processing. In this context, the flexibility may be understood as the facility of the central nervous system to reach different states of information processing from similar initial states ([15] p. 264). Consequently, enhanced EEG L1 values in response to affective induction may express the increased flexibility of information processing for neuronal assemblies, underlying the involved cortical regions [9,15].

We may conclude that both the K2 and L1 non-linear measures are sensitive to EEG changes during affective induction. Nonetheless, future EEG studies will have to clarify whether both K2 and L1 dynamical measures participate in specific positive versus negative valence discrimination, as happens with the EEG DCx measure [4]. In any case, relying on the obtained findings, it may be assumed that increased cortical dynamics, up to a certain level (see also [2,4]), are probably necessary for emotion functioning.

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