Human Electroencephalogram Induces Transient Coherence in Excitable Spatiotemporal Chaos

Gerold Baier,[1] Ron S. Leder,[1,2,3] and P. Parmananda[1]
[1]*Facultad de Ciencias, Universidad Autonoma de Morelos, Colonia Chamilpa, Cuernavaca, Morelos, Mexico*
[2]*Facultad de Medicina, Universidad Autonoma de Morelos, Colonia Chamilpa, Cuernavaca, Morelos, Mexico*
[3]*Department of Electrical Engineering, University of Wisconsin, Madison, Wisconsin 53706-1691*
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A time series from a human electroencephalogram (EEG) is used as a local perturbation to a reaction-diffusion model with spatiotemporal chaos. For certain finite ranges of amplitude and frequency it is observed that the strongly irregular perturbations can induce transient coherence in the chaotic system. This could be interpreted as "on-line" detection of an inherently correlated pattern embedded in the EEG.

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The detection of hidden transient patterns in cerebral activity as recorded by electroencephalogram (EEG), or likewise magnetoencephalogram (MEG), is an open problem. Remarkable changes in the complexity of patterns with time scales on the order of minutes are well known and can be characterized by statistical methods and methods from nonlinear dynamics (see, e.g., [1]). Direct evidence for more or less stationary low-dimensional behavior with stable correlations has been restricted to a few special cases such as EEG of slow-wave sleep [2,3] and of petit mal epileptic seizures [4,5]. Other sleep stages [3] as well as interictal and preictal activity have defied such a description and are often considered noisy even though correlations are obviously present [6] (see also [7]).

The application of measures from nonlinear dynamics like the calculation of dimensions and characteristic exponents is possible but the required stationarity of a considerably long time series is in general not fulfilled. Therefore care has to be taken when interpreting quantitative results for "attractors" in the cerebral activity. These concerns notwithstanding interesting results have been obtained when the dimensional analysis has been applied to short segments of EEG thereby stressing relative changes rather than absolute values [8]. Using a shifting time window of 20 s, Martinerie *et al.* found a significant decrease of the correlation density in intracortical signals prior to ictal activity that allowed them to predict epileptic seizures well in advance with good reliability [9]. Similarly, with a time window of 30 s, Lehnertz and Elger reported a significant decrease of a correlation dimension measure from recordings within the epileptogenic area before the appearance of statistically detectable changes [10]. These results are consistent with the view that the easily detectable ictal activity is preceded by a certain localized abnormal activity pattern with presumably increased correlations which so far cannot be detected in the EEG recorded from the scalp. In general, this local transient activity is (in integral measurements from the scalp) hidden within the high-dimensional activity of the rest of the brain and thereby escapes measures that require the evaluation of a long segment of EEG time series. As a complement to the quantitative measures that indicate the presence of significant short-term changes of EEG complexity, we propose a qualitative method to detect changes that are due to the appearance of transient correlated events in an environment with a high noise level.

A spatiotemporal dynamical system is deemed excitable if a local perturbation is enhanced to form a strong deviation from the nonexcited state and if this deviation is propagated throughout the medium. If a local perturbation is applied repeatedly, then a train of waves can be generated manifested as a spatiotemporally periodic pattern (see, e.g., [11] for a discussion of some biologically motivated equations). Commonly, in an excitable system the nonexcited state is a stable fixed point attractor. In this contribution, we extend the notion of excitability to a system whose unperturbed state is deterministic chaos. Spatiotemporal chaos can be characterized as a dynamic state of the system which is devoid of long-range spatial and temporal coherence due to continuous local divergence in the behavior of neighboring sites [12–14]. Thus, such a system will inherently prevent, rather than support, the propagation of isolated local perturbations. If, however, the chaotic state is composed of excitable units, i.e., if the perturbation of one site leads to a significant deviation from the nonexcited behavior (e.g., in amplitude), then repeated local perturbations of appropriate amplitude and frequency can lead to a wave train similar to the case where the unperturbed state is an excitable fixed point [15]. Because of the chaotic nature of the unperturbed state, such a system is expected to exhibit unique responses to nonperiodic and nonstationary local perturbations. We employ an electroencephalographic time series with broadband frequency distribution as an ongoing perturbation and demonstrate how an excitable spatiotemporal chaotic system can distinguish between different sections of the strongly irregular time series.

We simulate a model equation which is composed of coupled nonlinear oscillators. An oscillatory unit obeys the following reaction-kinetic expression:

$$\frac{1}{w}\dot{U} = -f(U,V) + V - 0.8U + a(1 - e\Omega),$$
$$\frac{1}{w}\dot{V} = f(U,V) - V, \quad (1)$$

where $f(U,V) = m_2 U/(1 + U) + m_3 U^2 V/[(0.81 + U^2)(0.8 + V)]$. Ω is the external perturbation which is applied only to one site of the spatiotemporal system; i.e., $e = 0$ for all other sites. These kinetic terms were originally introduced to describe the action of cellular calcium ions in response to external stimulation [16].

In the absence of coupling, each unit is in a period-one oscillatory state. Introducing linear diffusive coupling between nearest neighbors and imposing zero-flux boundary conditions for a one-dimensional array of 100 oscillators creates a spatiotemporal system. Parameters were chosen such that the dynamics of the spatiotemporal system is maximally chaotic (with a maximum number of positive Lyapunov characteristic exponents).

For this system it was found that an external periodic perturbation of the first oscillator leads to the induction of a globally coherent state for certain ranges of stimulation frequency [15]. This coherent state consisted of periodic waves with an amplitude considerably larger than the amplitude of the nonexcited chaotic oscillations. Moreover, it was possible to use deterministic chaos as a local perturbation to obtain an almost periodic state when the mean frequency of the chaotic oscillations was adjusted appropriately [15].

We studied the response of the above spatiotemporal chaotic system locally perturbed by a human EEG time series. The EEG (monopolar derivation C3/A2) was obtained from a noncomplaining male subject lying in bed in stage 2 sleep. Data were sampled at 100 Hz and band-pass filtered from 0.5 to 45 Hz. The recorded time series was deliberately chosen such that it did not contain discernible regular patterns or pronounced singular occurrences such as sleep spindles. The EEG signal was added to the first oscillator of the spatiotemporal model with coupling constant e. As a relevant parameter the model speed w was varied to change the frequencies of the intrinsic oscillations of the model relative to the EEG time series. All other parameters were left unchanged.

The model oscillators exhibit "excitability" in the sense that they respond to a suprathreshold perturbation with one large amplitude excursion before returning to their chaotic state. Thus, large amplitude excursions are frequently induced in the first oscillator which is subject to permanent perturbations. Because of the exponential divergence in the system introduced by the diffusive coupling, such large amplitude events are, in general, not supported by the medium and tend to die out unless reinforced by further stimulation at correct intervals. However, there are sections of the EEG time series which do support the propagation of waves into the medium at certain relative

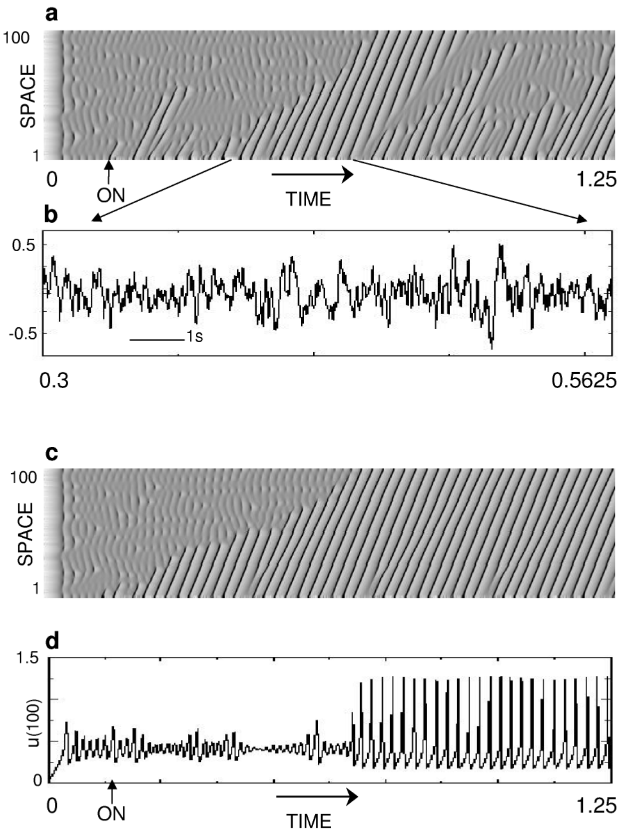

FIG. 1. Simulation of 100 diffusively coupled oscillators [Eq. (1)] with zero-flux boundary conditions and external perturbation of first oscillator. Parameters: $w = 420$, $e = 6.0$, $a = 0.325$, $m_2 = 20.0$, $m_3 = 23.0$. Gaussian white noise is added to all oscillators (root-mean square amplitude = 0.001). Time units are model time. (a) Grey-coded space-time plot of 100 oscillators perturbed by 45 s of human EEG. Perturbation started at the time indicated by an arrow. (b) Section of EEG time series (10.5 s real time) that induces coherent wave pattern (amplitude scaled by a factor of 10^4). (c) Space-time plot with time scale as in (a) except that perturbation consists of repeated sections shown in (b). (d) Time series of the last (100th) oscillator in the simulation of (c).

frequencies. Figure 1a shows a simulation at a constant model speed. It can be seen that the local stimulation initiates wavelike changes in the otherwise chaotic system at several occasions and one such set of waves succeeds in propagating through the whole array of 100 cells.

The simulation of Fig. 1a was performed with a low level of superimposed Gaussian white noise. We found that the observed transient coherence is also induced in the absence of noise but there exists an optimal level of noise that supports the spreading of the wave train through the entire medium increasing the number of waves that successfully propagate through the medium.

This optimal noise level also increases the robustness of the occurrence of transient coherent waves. The result in Fig. 1a is qualitatively maintained for different initial conditions of the model system; i.e., it does not depend on a particular phase relationship between perturbation and model dynamics. There exists, however, a minimum perturbation amplitude below which no transient waves are induced. In some cases it was observed that the induced waves disappear when the perturbation of the first oscillator is too strong. Thus, in general, there exists a finite window of both frequency and coupling strength for which the induced waves propagate through the whole system, and this window is enlarged in the presence of an optimal level of white noise.

Figure 1b shows the section of EEG time series that is responsible for the induction of transient coherence. The section does not contain any obvious features suggesting the presence of a particular pattern. Neither inspection by eye nor Fourier analysis reveals any qualitative differences between this section and other sections of the same time series that do not induce the spreading of large amplitude waves.

We picked the section of Fig. 1b and created an extended time series composed of replicas of this section. This artificial time series was then applied as a perturbation to the first oscillator with parameters as before. Figure 1c shows the result. The time series with repeated copies of the section in Fig. 1b induces global coherence in the spatiotemporal chaos. It can be seen that this behavior is robust in the sense that initial inhomogeneities (caused, for example, at the point of cutting of the repeated sections) are overcome and the waves tend to homogenize themselves. As a result, the time series of the last oscillator (Fig. 1d) shows a clear switching from the chaotic oscillation of the unperturbed system to the large amplitude oscillations created by the traveling waves. If the section chosen for repeated stimulation was significantly longer than the one displayed in Fig. 1b, no global coherence could be induced.

Scanning the speed of the model, we found that another section of the EEG time series induced transient coherence similar to that shown in Fig. 1a at a different model speed. Again, choosing the corresponding section of the time series and applying it repeatedly led to global coherence in the model.

As a control simulation, we perturbed the first oscillator with a time series of Gaussian white noise with equal and up to 3 times the mean amplitude as the EEG time series but did not observe induced transient coherence in these cases.

In this somewhat unusual approach an experimentally recorded time series is used as an input to a differential equation. Rather than explicitly analyzing the time series, we thus let the model's complex spatiotemporal dynamics perform the analysis. The differential equation contains the following features that make it suitable for such a treatment: (i) The unperturbed state has mixing properties (i.e., positive Lyapunov exponents) therewith preventing short-term excitations from spreading over the entire array of coupled oscillators. (ii) The perturbed system is a "decision maker" by means of a divergence that distinguishes the incoherent state of low amplitude chaos from a coherent (periodic) state with large amplitude. The decision can be provoked by patterns of proper frequency embedded within the perturbation. (iii) The large-amplitude wave pattern is not a stable solution of the unperturbed model with a zero-flux boundary condition. Also we did not find evidence that there exists an unstable periodic solution of corresponding amplitude and frequency under these conditions. The wave pattern is a stable solution of the unperturbed model with periodic boundary condition, however. This might help to explain why continued perturbation of the boundary condition suffices to induce this pattern in this system. (iv) If a suitable pattern within the external time series is transient, it induces large amplitude waves but the model returns to the former chaotic state when the match is lost. If the suitable pattern is repeated over and over, the model reaches and subsequently stays in the globally coherent state. (v) The most striking feature, as detected in [15], is that the local perturbation required need not be periodic. It is sufficient that a sequence of proper stimulations occurs within certain periods of time. Once the wave pattern is induced, the system tolerates an occasional missing stimulus without dissolving into the original chaos of the system.

Local induction of periodic wave patterns was also observed in other reaction kinetic models with spatiotemporal hyperchaos (e.g., those described in [17] and in a spatiotemporal version of the FitzHugh-Nagumo equation, see [18,19]). However, in all successful cases the kinetic oscillator contained at least one autocatalytic term; i.e., it contained at least one positive contribution to the trace of the Jacobian matrix. An oscillator without autocatalysis which also generates spatiotemporal hyperchaos in a diffusion-coupled arrangement [20] did not show any tendency to form coherent patterns when stimulated locally [18]. For the parameter region studied this oscillator does not show excitability of the limit cycle created in a supercritical Hopf bifurcation. The crucial features common to the isolated kinetic oscillator Eq. (1) and the other successful systems is the preserved excitability beyond the supercritical Hopf bifurcation.

For a number of spatially extended systems, transitions from chaotic to periodic patterns have been achieved by means of external perturbations, e.g., applying parametric disorder to coupled units of forced, damped, nonlinear oscillators [21], subjecting a continuous system of coupled oscillators to strongly resonant forcing [22], and appropriate periodic forcing of a nonlinear-drift wave equation [23]. However, in these and other cases the external perturbation had to be applied to all sites at the same time to achieve global control of the pattern, whereas in the present case the perturbation of one site suffices to induce the long-range ordered pattern.

The finding that an optimal noise level supports the spreading of waves into the chaotic medium bears some resemblance to the experiments by Kadar *et al.* [24] who reported a noise-supported traveling wave front in a subexcitable steady state system at an optimal noise level. However, in our case the transient wave patterns also form and spread in the absence of any noise and thus the main cause of support seems to come from the intrinsic deterministic dynamics.

The main difference between an excitable chaotic system and an excitable fixed point is that the fixed point system requires a single suprathreshold perturbation to generate a traveling wave, whereas the chaotic system requires a sequence of correlated perturbations, i.e., a pattern, for coherent excitations to propagate. Thus the excitable chaotic system is suitable to act as an on-line pattern recognition device. It provides, paraphrasing from Rieke *et al.*, "… a sort of running commentary…" to a "… world of random but correlated time dependent signals." [25]. As an extension of this, it is conceivable that an excitable chaotic system could be "trained" to search for specific short-term correlated events. That would open the possibility to, e.g., detect abnormal activity of an epileptogenic center prior to an epileptic seizure in EEG or MEG recordings.

Finally, we would like to mention that natural sensory input to the brain is known to induce coherent transient responses of previously disordered neuronal assemblies, e.g., in the visual cortex [26], the olfactory bulb [27], and the auditory cortex [28]. These transient coherent responses have been proposed to be connected with the process of cognition [29]. Our numerical results could be considered to mimic a component of the underlying dynamics of that transient coherence.

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