

Noise-induced first-order phase transitions in chaotic brain activity**Walter J Freeman****International Journal of Bifurcation and Chaos 9, No. 11 (1999) 2215-2218**

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Abstract

Brain electrical activity in animals during normal behaviors has aperiodic wave forms that suggest its origin in chaotic dynamics. Attempts using low-dimensional, deterministic chaotic models to prove that pulse trains and electroencephalographic (EEG) waves are chaotic have not succeeded. The assumptions of autonomy, stationarity, and noise-free operation that are needed to define the attractors and their embedding dimensions in these models have been shown not to hold for brains. Numerical estimates of correlation dimensions and Lyapunov exponents have failed to converge to normative values. Analysis of EEGs from sensory cortices show that a very different model applies to brains, which is more closely related to lasers than models of twist-flip maps and reaction-diffusion systems. Neurons interact with each other through axons with nonlinear, amplitude-dependent gains, by which they form fields of white noise. When the strengths of interactions among neurons are increased by input from receptors, the neurons interact more strongly and lose their high degrees of freedom. The macroscopic constraint that is imposed on their activity by sparse global coupling appears as an order parameter in the form of spatially coherent but indeterministic, stochastic chaos.

1. Introduction

The broad spectra and aperiodic oscillations that are observed in recordings of brain activity in waking and sleeping states have suggested to many researchers the possibility that this activity is generated by nonlinear dynamic systems governed by chaotic attractors. This interesting hypothesis has been pursued over the past 15 years mainly with the aid of models derived from deterministic chaotic systems, such as reaction-diffusion systems and those with twist-flip trajectories, the Lorenz, Rössler and Chua attractors. Efforts to estimate the correlation dimensions and the values of Lyapunov exponents using the Grassberger-Procaccia and related algorithms, have been highly successful in the low-dimensional systems. This success has led to

efforts to model the cognitive functions of sensory cortex in the realm of pattern classification using networks of chaotic elements that are coupled by nearest neighbor or next to nearest neighbor weighted connections. The proper response of such systems would be convergence to synchrony or phase locking of the array into one of a set of global chaotic attractors, after suitable training to form the attractor landscape.

Attempts to calculate correlation dimensions and related values have not succeeded in converging to reliable numbers [Rapp, 1993; Freeman & Jakubith, 1993]. The failure is partly due to an inappropriate assumption that the stationarity and autonomy of the models holds also for brain systems. More importantly, the methods fail because the signals taken from brains are heavily invested with various kinds of noise, including white, pink and brown.

My view is that approaches using networks of deterministic chaotic modules are inadequate for describing and modeling brain chaos. There are a few circumstances when these assumptions hold to a reasonable approximation, including some types of epilepsy, dementia, surgical isolation of brain subsystems, and immobilization with drugs to give a degree of autonomy and stationarity. However, under no normal conditions is brain activity free of noise, that is, additive components of the activity that are for all useful purposes infinite in dimension, near zero under time or space lagged correlation, and nearly flat in power spectrum. The point I wish to make is that noise is not only unavoidable but is required for normal brain operations.

This view does not rule out chaos, but only the class of models that has been most commonly advanced to prove its existence and explain its origin in brains. Instead, I propose an alternative view, that chaos emerges through the interaction of noisy neurons, such that by their constraining influence on each other in large masses, their degrees of freedom are diminished. Then the population activity can be viewed as an order parameter that directs or 'enslaves' [Haken, 1991] the activities of the component neurons.

This order parameter can be modeled with ordinary differential equations within certain limits [Freeman, 1992, 1994; Chang & Freeman, 1998; Kay, Shimoide & Freeman, 1995], but it cannot be readily distinguished, it at all, from colored noise [Rapp, 1993], like that seen in Brownian motion or in telegraph noise. However, this kind of dynamics can be seen to endow brains with some of their most important properties, which include the stable maintenance of the aperiodic basal activity that neurons require to stay alive, the capacity for exceedingly rapid global state transitions from readiness to action in any direction, and the ability to generate creative behaviors, which cannot be accessed with point or limit cycle attractors, or by reliance solely on random stochastic processes.

2. Experimental Evidence from Electroencephalograms (EEGs)

Local areas of sensory cortex (visual, auditory, somatosensory and olfactory) generate aperiodic waves of potential deriving from the flow of dendritic currents across the extracellular resistance of the cortical tissue. The oscillations are in the range of 1 to 100 Hz with $1/f^n$ spectra, where $n \sim 2$ [Barrie, Freeman & Lenhart, 1996]. Simultaneous recordings from multiple sites with arrays of surface electrodes as EEGs demonstrate that the activity has the same wave form over areas ~ 0.5 - 1.0 cm or more in diameter. Such areas include millions of excitatory and inhibitory neurons, whose interactions generate the EEG oscillations by negative feedback. The amplitude modulation (AM) of these spatially coherent waves in brief time segments lasting ~ 100 ms gives spatial patterns that are determined by the synaptic connectivity in each cortex. The AM patterns

are observed in awake, motivated animals, which have been trained to identify and respond to sensory conditioned stimuli that elicit conditioned responses. The synaptic connections between the excitatory neurons can be described with an association matrix of the kind modeled by Kohonen, Hopfield, Anderson, Amari, and others. The weights change selectively when the animals are trained to identify significant stimuli. The learning establishes attractor landscapes in the sensory cortices, with a basin of attraction for each class of stimuli that the animals have learned to identify. The basins of attraction are continually re-shaped by experience, and each attractor is accessed by the arrival of a stimulus of its learned class.

Formation of a spatial pattern corresponding to the classification of a stimulus is by a first order phase transition comparable to going from a liquid to a solid phase. Each new state lasts about 50-200 ms.. The onset and offset of spatial patterns in each cortex is at time intervals ~ 100 to 200 ms, so that a perceptual sequence changes discontinuously like frames in a cinema film.

Phase transitions do not happen instantaneously at all locations in the distributed medium formed by the cortical neuropil, but require ~ 5 -6 ms. Measurement of the phase of the dominant temporal frequency in the carrier wave form of each AM pattern at each of 64 recording sites in an 8x8 array of electrodes (spacing 0.5 to 0.8 mm, window size 4x4 to 7x7 mm) reveals a radial phase gradient in the form of a cone. The location and sign (maximal lead or lag) of the cone vary randomly from each spatial pattern to the next. The spatial phase gradients (in radians/mm) vary inversely with temporal frequency, but when they are converted to m/s, they are nearly invariant at the conduction velocity of axons running parallel to the cortical surface, about 1.8 m/s in the olfactory system [Freeman & Baird, 1987] and about 0.6 m/s in the other sensory cortices. At a typical frequency in the range of 40-80 Hz, the domain of commonality in a sensory area ~ 10 mm in diameter forms in a time period of less than 0.25 cycle, which is the half power level both for formation of the cooperative activity and its read-out under spatial integration. Thus the radial phase gradient defines the surface area of the interactive domains in cortex. These areas are known to be compatible with the "patches" found in brain images of humans using PET and fMRI during performance of cognitive tasks [Roland, 1993].

3. The Origin of Fields of White Noise in Cortex

The apices of the cones appear to mark the sites of nucleation for the state transitions in the excitable medium of the cerebral cortex. They show that the AM pattern with its aperiodic carrier wave form is a global property of the cortex. The random variation of the location of the apex irrespective of the content shows that the phase gradient contains no information. The random variation of the extremum shows that the phase transition is a kind of symmetry breaking. The persistence of the phase gradient through the perceptual event shows that the spatial patterns are based in broadly distributed couplings among neurons, and that the density of the coupling is too weak to enforce phase synchronization by entrainment, despite the emergence of a common carrier wave across the population.

Owing to the low coupling density, this carrier wave form is not readily seen in the pulse trains of the component neurons. Pairs of pulse trains appear to be uncorrelated between neurons [Abeles, 1991]. Each neuron appears to have pulse interval distributions that conform, at low rates, to a Poisson distribution with a dead time, and at higher rates, to a Gamma distribution of order one-half during the performance of learned behaviors. Prolonged time ensemble averaging is required to show that the probability of firing of each of the component neurons fluctuates with the same wave form as the population [Freeman 1992], provided that both the carrier wave and the pulse

train are recorded at the same spatial location of the cortex, and over the same time span (about 20 minutes of recording to get 10,000 pulses from a typical neuron firing at 8/sec).

An outstanding characteristic of virtually all neurons in normal brains is their continuous activity. Neurons must stay active in order to survive. However, isolated neurons are not active, unless they are artificially stimulated electrically or chemically. Although under such stimulation they can and do show periodic and aperiodic oscillations indicating the existence of limit cycle and chaotic oscillators, normally they are governed by point attractors. When alone they are silent. When in company their normal background activity is produced by the positive feedback of mutual excitation within cortex. Up to 85% of cortical neurons are excitatory, and most of their synaptic input comes from other excitatory neurons, with only 10% from outside the local neighborhoods.

The positive feedback creates a non-zero stable state for cortical neurons, which reflect the existence of a global point attractor [Freeman, 1996]. Indeed, when the neurons are driven by electrical perturbation away from their basal state, the transient change in pulse density is followed by an exponential decay to the pre-stimulus baseline, whether by excitation or inhibition. The decay rate decreases with decreasing perturbation amplitude. The rate extrapolates to zero at zero input, showing that on linearization of the system at its stable point attractor, one of the eigenvalues is real and zero; there is a pole at the origin of the complex plane [Freeman, 1975].

In other words, the cortical neurons interact by pulses, i.e. axonal action potentials, and the rates of firing are limited by the refractory periods of the neurons. This provides for the stability of the basal active state of the population they form by interacting. The nonzero point attractor is a population property, not an attribute of the individual neurons. The attractor provides a field of white noise in the 2-dimensional functional state space of the cortex. It is within this field that cooperative domains form, which, under read-out by spatial integration, stand out like the light of a candle on a dark night. That emergent coherence is the basis for pattern formation by the first order phase transitions.

4. Conclusions

Synchronization of "coupled chaotic oscillators" does not normally occur in brains. There are four reasons for this claim.

1. The neurons comprising the neuropil of cortex are sufficiently complex that they can generate periodic and aperiodic (chaotic) oscillations in their membrane potentials and pulse trains, but normally they do not. Their basal attractors are neither limit cycle nor chaotic. The neurons can be made to generate pulse trains that are periodic, if they are isolated or coupled in small networks and given chemical excitants, but their activities are nearly random when they are embedded in cortical neuropil. Owing to constant re-excitation by positive feedback interactions, a field of white noise emerges as a macroscopic property of the neuropil. If the interactions are spatially uniform, the activity appears as steady state mean firing of a population, with pulse density being governed by a non-zero point attractor.

2. Brain chaos arises when the neuropil contains both excitatory and inhibitory neurons, and the randomly firing neurons are constrained by their synaptic interactions to generate an oscillatory local mean field potential. It is recorded as the EEG. It has a $1/f^n$ spectrum, but the behaviorally relevant information is in a pass band in the gamma range: 20-80 Hz.

3. The EEG is embedded in noise. It is constrained noise, which makes it so difficult to distinguish from band-limited noise, a constraint of a different kind. Deterministic chaos as it is defined mathematically and by digital simulation [Freeman et al. 1997] does not exist in brains.

4. Coupling does not enforce entrainment into phase locking. Instead it leads to entry into states of order that are expressed in spatial patterns of amplitude and phase modulation. The synaptic coupling of multiple chaotic domains in the neuropil of cerebral cortex is not revealed in phase locking or synchronization at zero lag of local mean fields in the time domain. Phase transitions of brains into states of global order are expressed by the formation of spatial patterns of unsynchronized oscillations in the gamma range.

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