EEG evidence of 1st order phase transitions by neural populations in gamma activity of sensory neocortices of trained rabbits and cats

Walter J Freeman
Department of Molecular & Cell Biology, LSA142
University of California at Berkeley CA 94720-3200 USA
wfreeman@socrates.berkeley.edu

Abstract

Multichannel EEG recordings from trained animals with high-density epipial arrays of electrodes fixed on cortical sensory areas reveal spatiotemporal patterns. These patterns have the form of temporal modulations of the phase (PM) and amplitude (AM) of spatially coherent carrier waves with frequencies in the gamma range. The patterns form and dissolve at rates in and below the theta range. AM patterns serve to classify EEG segments with conditioned stimuli (CSs). Phase patterns (radially symmetric) show episodic synchronization. Fine temporal resolution of the analytic phase using the Hilbert transform indicates that pattern formations are by 1st order phase transitions.

Report

Domains of cooperative neural activity called 'wave packets' (Freeman 2000) are found in the visual, auditory, and somatosensory cortices of rabbits trained to discriminate conditioned stimuli in these modalities (Figure 1). Each domain forms by a first order state transition, which strongly resembles the phase transition from vapor to liquid. Raw sense data carried to cortex by sensory axons drive cortical action potentials in swarms like water molecules in steam. The increased activity destabilizes the cortex. Within 3 to 7 milliseconds of onset, the activity binds together into a scintillating liquid state, like a rain drop, which holds for 80 to 100 milliseconds, then dissolves. The size of the wave packets, 10 to 30 millimeters in diameter in rabbits, is determined by the conduction velocities of the intracortical axons by which the cooperative activity is maintained. Wave packets form at rates of 2/second to 7/second, overlapping in space and time (Freeman 2002).

The results of sensory information processing are expressed in spatial patterns of amplitude modulation (AM) of the local field potentials. They oscillate in the gamma range (20 to 80 Hz in rabbits). The AM patterns are seen in EEG potentials generated by dendrites and recorded with high-density 8x8 electrode arrays. Figure 2 shows representative traces from a single trial while recording from the olfactory bulb or visual cortex. The superimposed trace shows the pattern of respiration, which is correlated with the theta activity in the bulb but not with low frequency activity in the visual cortex. The AM patterns (Figure 3 A, B) correspond to the categories of conditioned stimuli that the rabbits can discriminate.

The state transition by which AM patterns form is manifested in the spatial pattern of phase modulation (PM), which has the radial symmetry of a cone (C, D). The apex of the PM cone marks the site of nucleation of the AM pattern. The phase gradient gives a soft boundary condition, at which the axonal delay in spread gives sufficient phase dispersion to reach the half-power level (Figure 1). Figure 4 shows an example is shown from the visual cortex of the temporal locations of the starting times of stable phase cones in a set of 40 trials. The successive cones on each trial are shown on alternating pairs of lines. The duration of each bar indicates the number of steps over which the phase cones existed; the actual duration would be indicated by adding 32 bins (64 msec) to each bar. Cospectra between EEGs and phase cones showed strong peaks in the delta and theta ranges (Freeman 2002).

Differences in analytic phase for a given pair of channels are plotted in Figure 5 for several channel pairs, for one trial (cat data). These showed emergent phase differences between channels having the form of plateaus punctuated by abrupt changes nearly simultaneously on multiple channels. The direction of the jump varied at random irrespective of prior jumps, so the differences did not increase monotonically. This pattern was predicted from prior measurement of phase cones, in which the location and sign of the apices varied randomly (Freeman 2002) and so also the direction of the phase gradient between each pair of electrodes.

The findings show that significant cortical activity occurs in the form of mesoscopic interactions of millions of neurons in broad areas of cortex, which are more clearly manifested in graded dendritic potentials than in action potentials. The distinction is analogous to the difference between statistical mechanical and thermodynamic descriptions of particle behavior. Both manifestations of neural activity show spatial and temporal discontinuities but at distinctive scales of microns and milliseconds versus millimeters and tenths of a second.

Figures

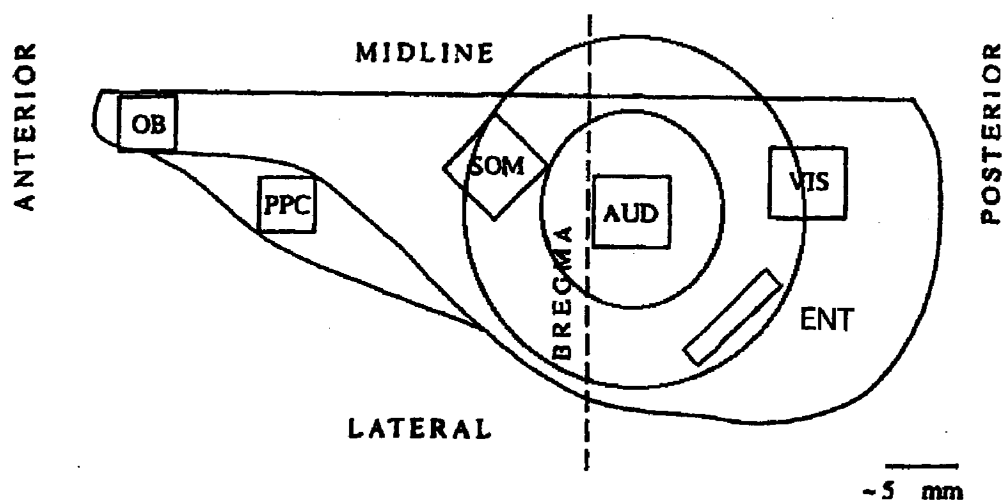

Figure 1. The outline shows the left cerebral hemisphere of the rabbit as seen from above. The rectangles show the approximate locations of the 8x8 arrays plaed on the olfactory bulb (OB), prepyriform cortex (PPC), somatomotor cortex (SOM), auditory cortex (AUD), and visual cortex (VIS), and a 2x8 array on the entorhinal cortex (ENT). The inner circle shows the modal diameter of phase cones. The outer circle shows the diameter including 95% of cases. The vertical line is the zero stereotaxic reference. Adapted from Barrie et al. (1996).

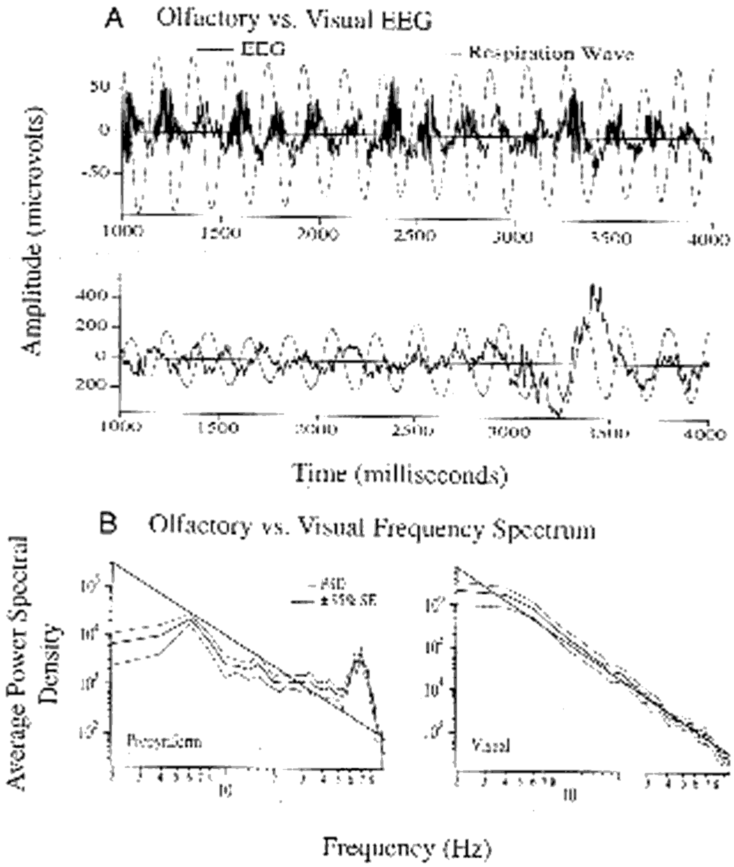

Figure 2. The bulbar spectrum shows peaks in the theta and gamma ranges. The visual cortical spectrum shows a $1/f^2$ fall in log power with log frequency. From Barrie et al. (1996)

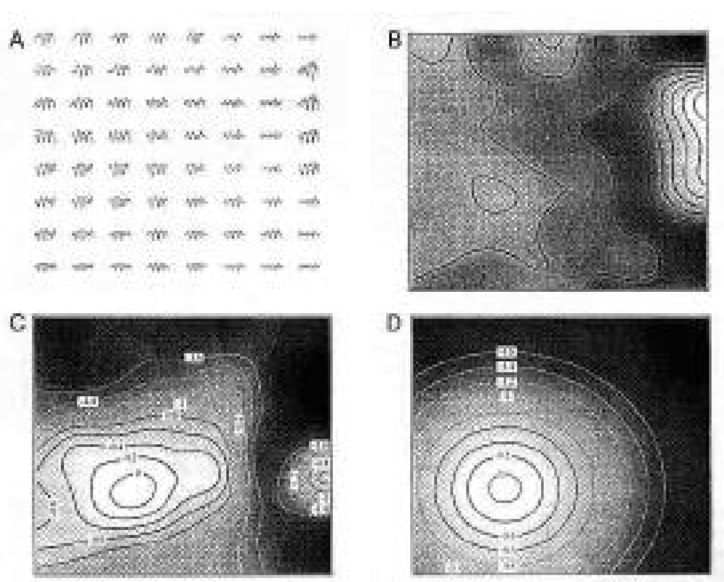

Figure 3. **A**. EEG traces from an 8x8 electrode array (6x6 mm) in a representative 64 msec segment from visual cortex after band pass filtering in the gamma range (20-80 Hz). **B**. Spatial AM pattern from RMS amplitudes. **C**. Spatial PM pattern at the peak frequency. **D**. A cone was fitted to the phase values. From Barrie et al. (1996).

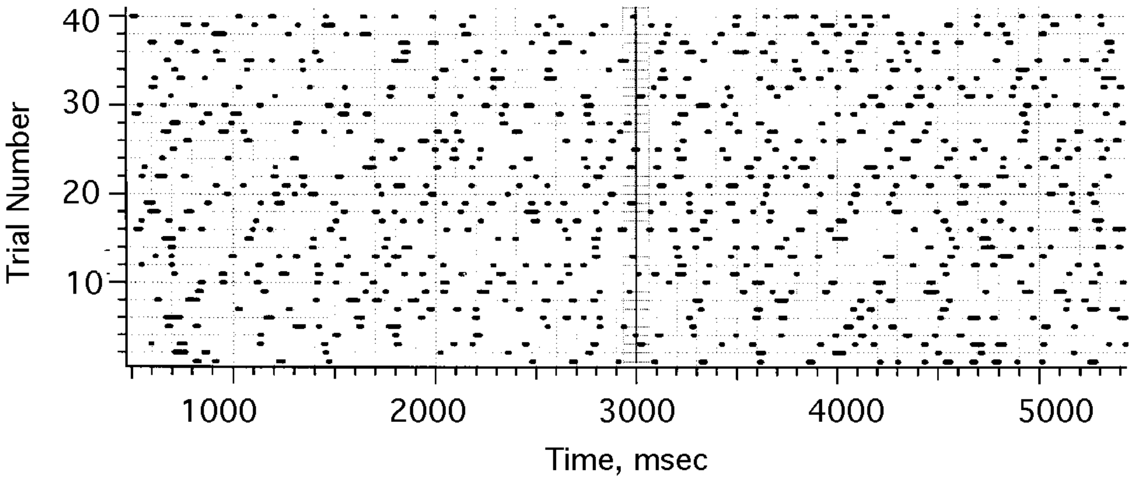

Figure 4. Phase cones are equally likely to occur pre- and post-stimulus. From Freeman (2002).

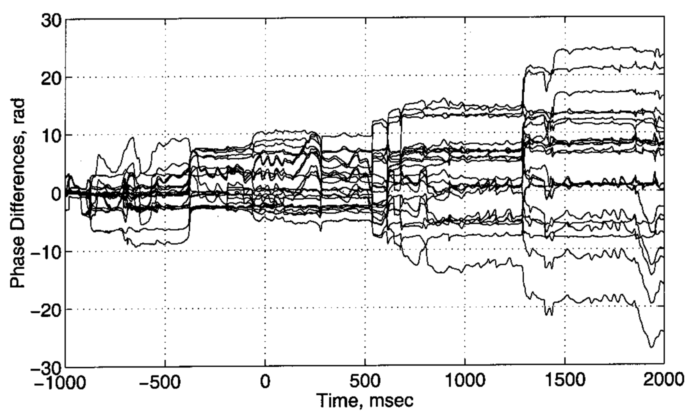

Figure 5. From Freeman and Rogers (2002)

References

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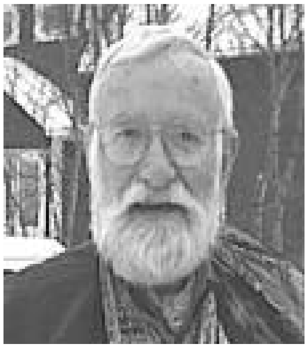
About the author



Walter J Freeman studied physics and mathematics at MIT, medicine at Yale (MD *cum laude* 1954), internal medicine at Johns Hopkins, and neurophysiology at UCLA. He has taught brain science in the University of California at Berkeley since 1959, now as Professor of the Graduate School. He received the Pioneer Award from the Neural Networks Council, an NIMH MERIT Award 1990, was President of the International Neural Network Society in 1994, and is Fellow of the IEEE. He authored >400 articles and 5 books including: "Mass Action in the Nervous System" (1975) and "How Brains Make Up Their Minds" (2001).