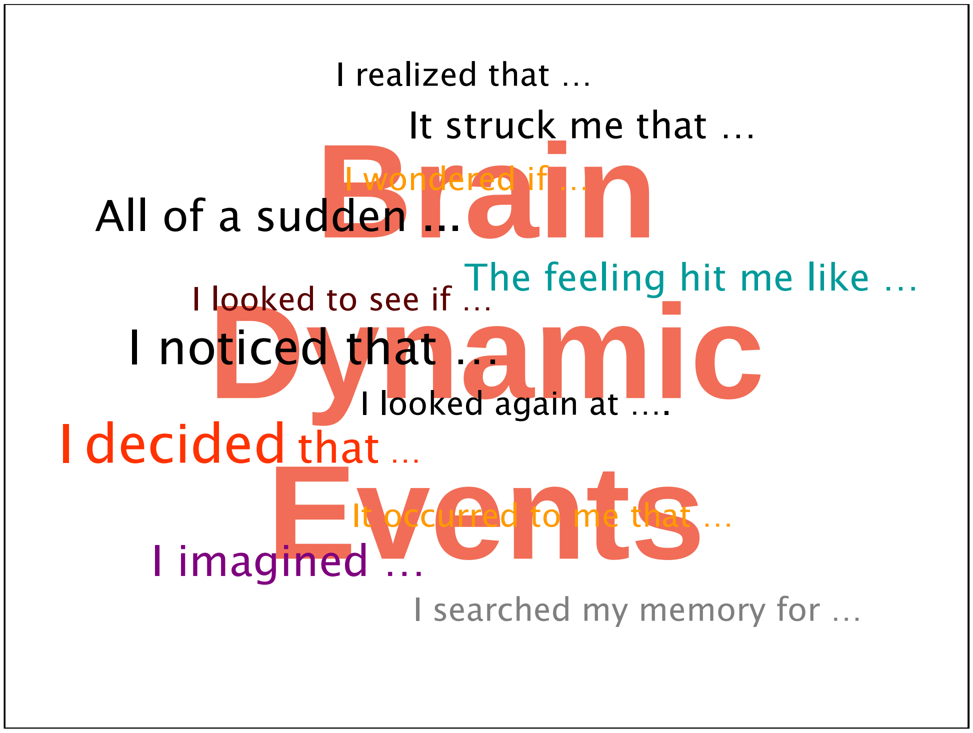
Talk given at the workshop on Brain Communication, Banbury Center, NY in May, 2004.



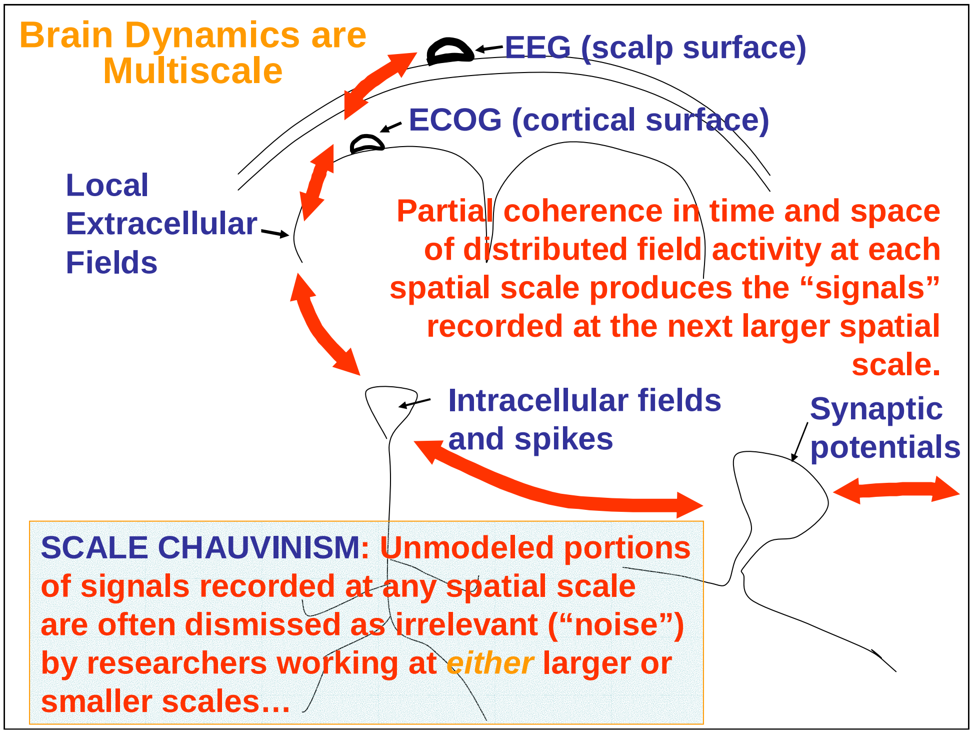
Cognitive events directly involving little or no motor behavior have distributed consequences for redirection of attention, memory retrieval, etc. – and thus should be supported by distributed brain events.

Multiscale Brain Communication

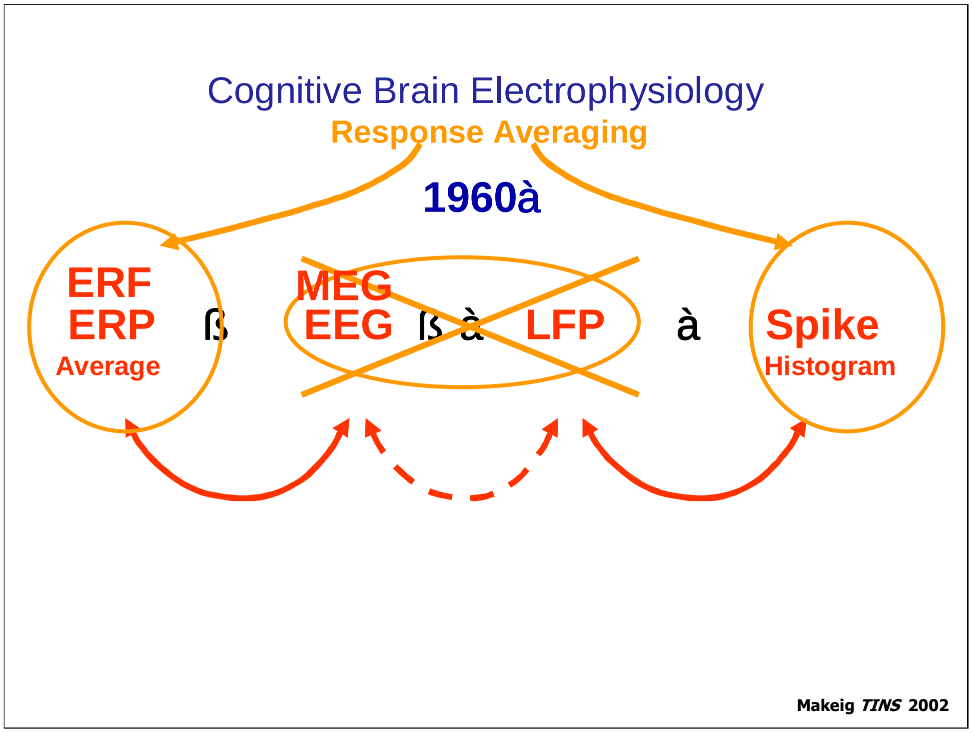
- Biasing of spike synchrony by extracellular field potentials may occur at different spatial scales, with different effects.

The spatial scale(s) of partial synchrony giving rise to scalp-recorded fields are not known, but may be extracted from multiscale recordings.

Brain communication ***must*** be multiscale. However, surprisingly little data on multiscale brain dynamics have been recorded.



Scale chauvinism (Edmund Wilson) is a sociological fact…



The advent of response averaging helped split the field of brain electrophysiology in two distant camps – those who average scalp potentials (ERPs) and those who study spike trains of single neurons. Currently, new and accelerating streams of results are linking ERP and EEG processes (e.g. using event-related coherence), on one hand, and spikes and local field potential oscillations (in awake behaving animals) on the other. A still-missing link is the connection between the <1-cm^2 coherence domains of local cortical field potentials (LFPs) and the (>1-cm^2) EEG coherence domains. Bridging these gaps in modeling nad observation may at last unify the field of brain electrophysiology.

How Does Info Transmission in Brains Work?

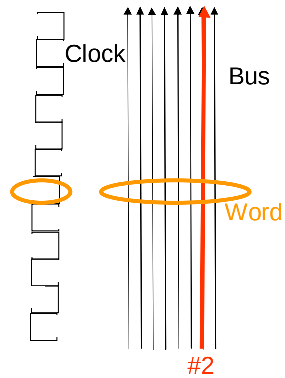
Info transmission in computer

Information transmission via **bits in a word**

computer word = **synchronous** bits on bus

The bit stream on any line has little meaning.

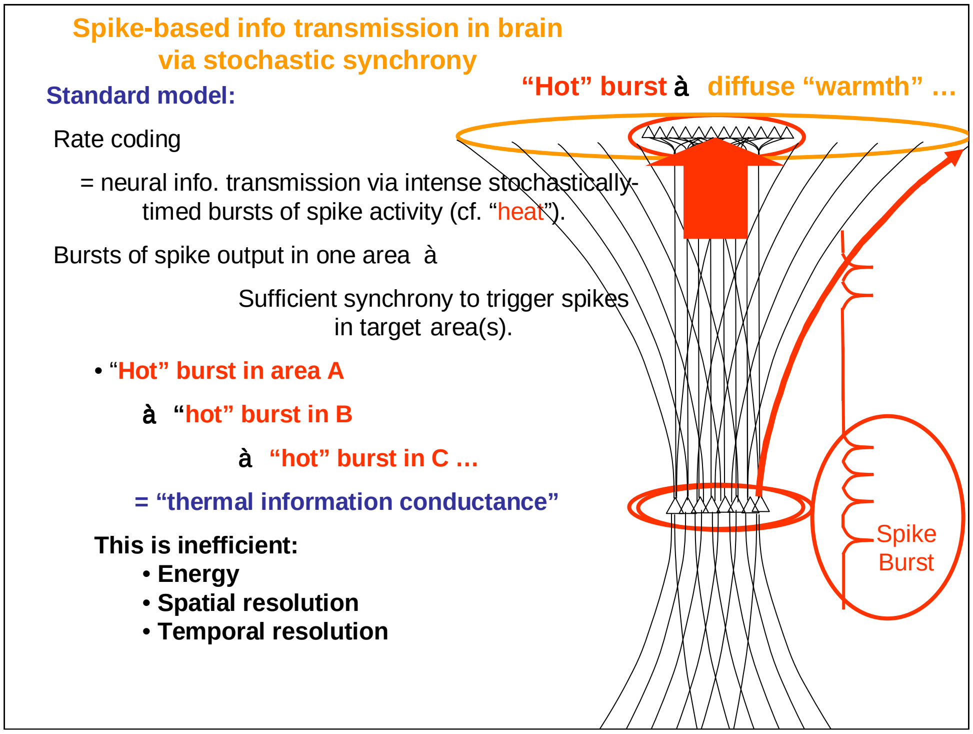
- Fixed, labeled lines (fixed bus)
- Single, external clock



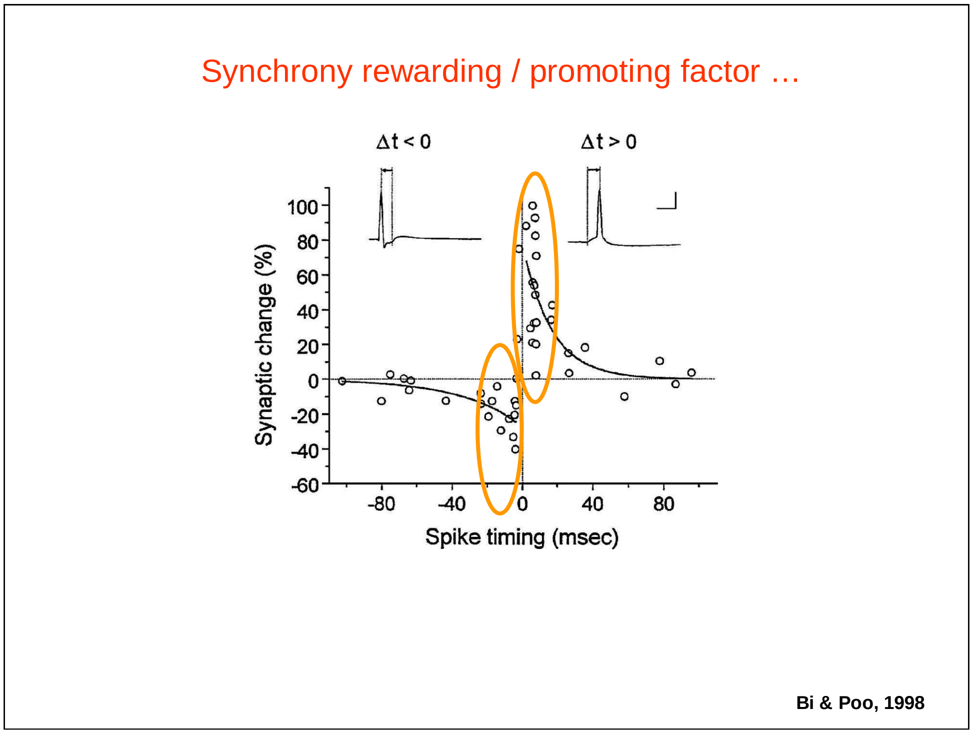
Current computers transmit and store information as words distributed across a 'bus' – Information transfer involves sending and receiving volleys of bit state events, synchronized by a central clock.

In this context, a bit event on a single line of the bus has no meaning. Instead, meaning is associated with the synchronous **word** transmitted across the computer bus.

What is the brain correlate of the computer word?

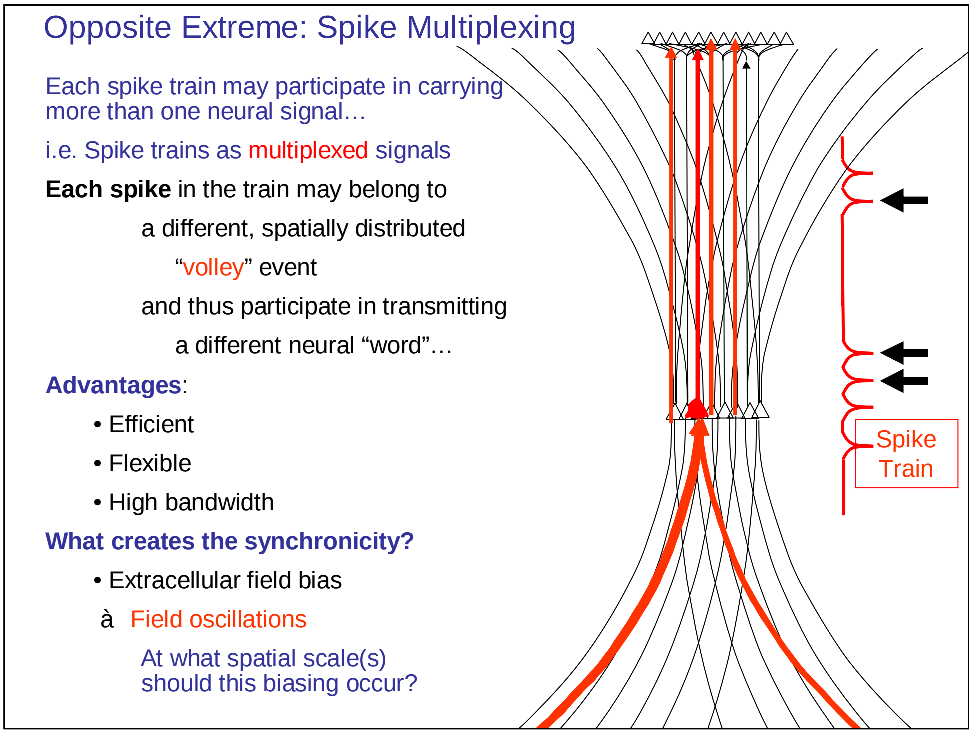


The theory that long-distance communication in the brain is via a spike rate code (in which rapid bursts of (input) spikes code for events) amounts to a "thermodynamic" view of information transfer as thermodynamic "information conduction." Unfortunately, this model of information flow is not efficient enough to be the whole story of brain communication.



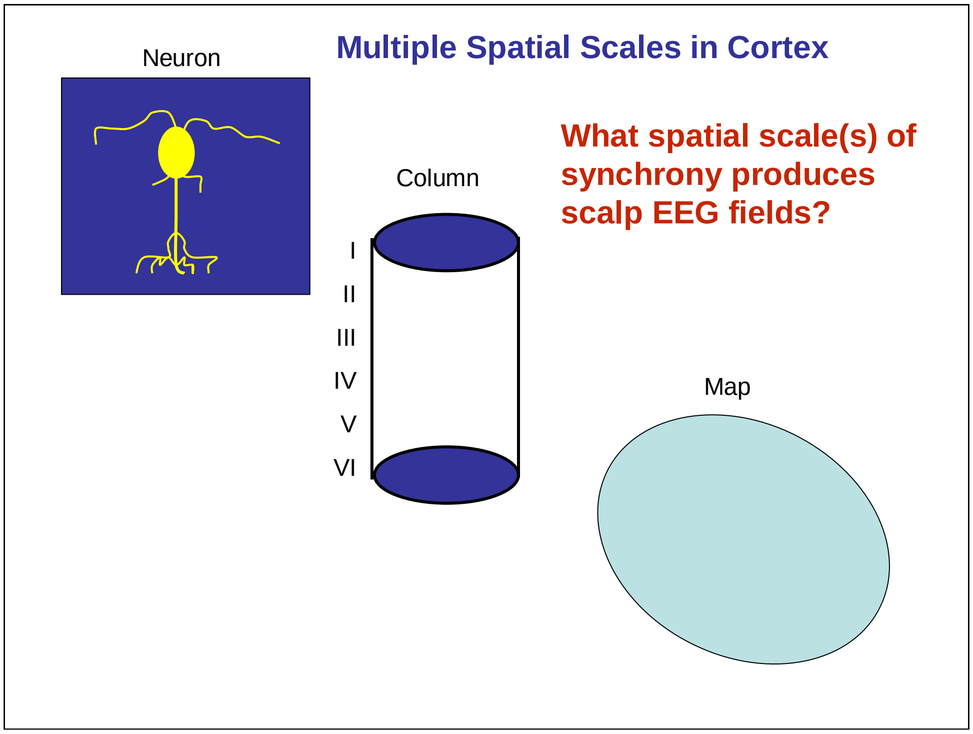
The fact of spike time dependent learning should shape neurons to respond to spatially distinct, near-synchronous neural **input volleys**, each involving a small fraction of the 5,000-10,000 input synapses of the typical pyramidal cell in cortex.

These input volleys (or input volley events) are the most natural correlate of computer words.



At the opposite extreme, one might imagine a brain in which every (input) spike is part of a near-synchronous, spatiotemporally organized (but spatially distributed) **input volley**. In this view, spikes in single neurons are like bit events in a computer bus. Coding of information transferred on a computer bus is normally carried by synchronous words (bit patterns across the bus), synchronized by an external clock.

In the brain, the ‘bus’ may be different for every message. Time-specific learning mechanisms allow neurons to learn to respond to multiple, spatially distinct (but possibly overlapping) synchronous input volley events. Their (output) spikes, through the same learning process, also have meaningful effects only as a part of the distributed (output) volleys they participate in.

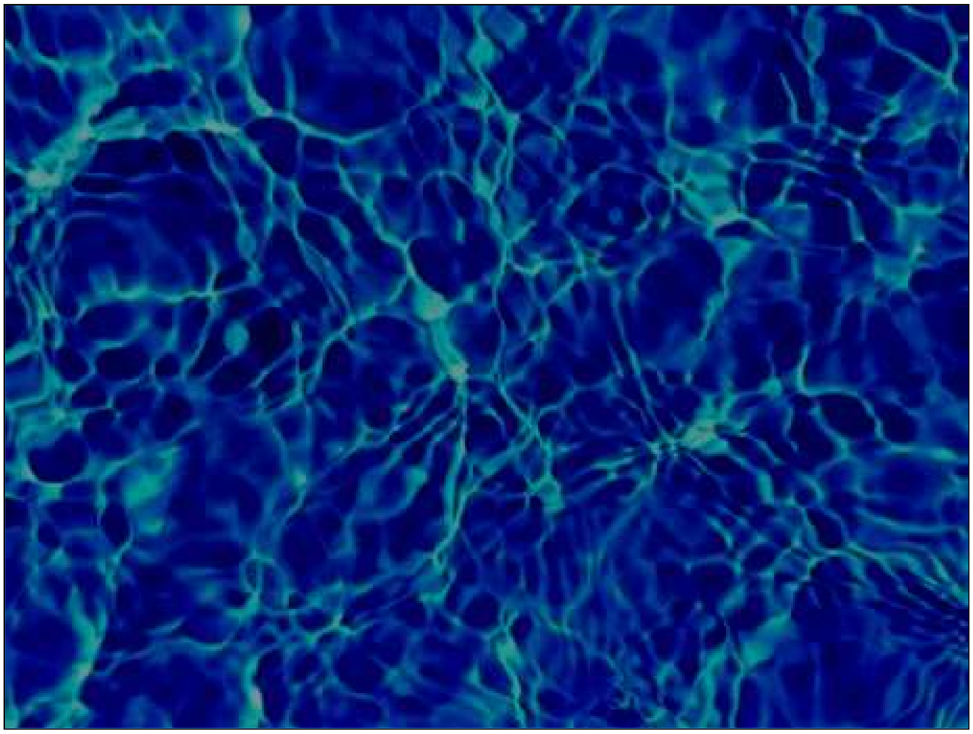


Surprisingly little research has been done to address the question above …

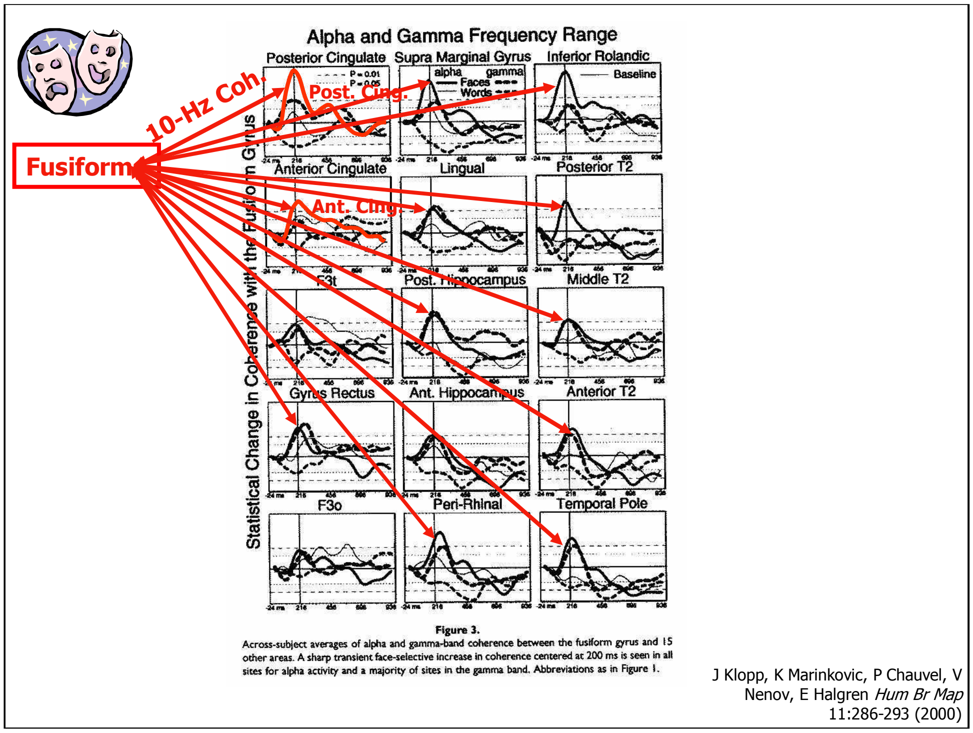
Emergent non-linear dynamic phenomena are seen at every spatial scale and medium ...

Organized field activities are also coherent, spatially organized phenomena in the electrical ‘space’ of the cortex.

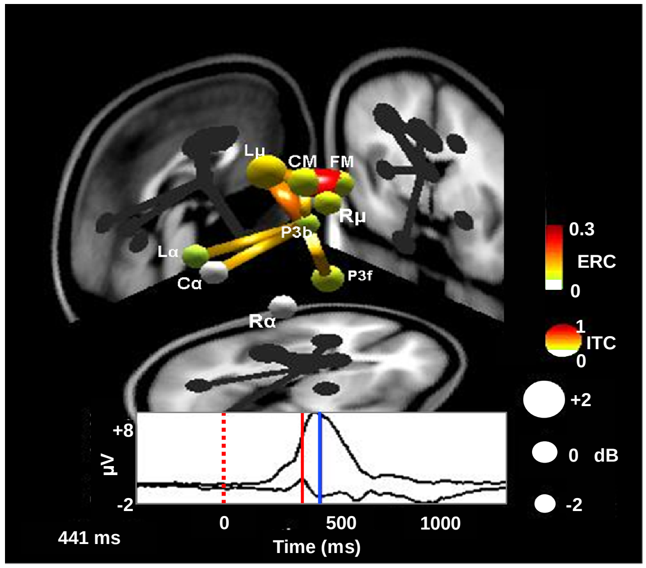
The neuroscientist Walter Freeman (UC Berkeley), through decades of observing local field patterns on the cortex of animals using 3-mm (8X8) grids, believes that coherent field activities on cortex have a spatial structure similar to the concentric ripples created by rain drops on a pond. These may be outgoing or ingoing, may overlap, and may be at different frequencies (etc).



Much more complex patterns of spatiotemporal dynamics are available in coupled nonlinear dynamic systems (such as these swimming pool ripples produced by wind and border reflections). However, generative models of cortical activity, or more adequately of cortical-thalamic activity, still involve many free parameters, and in the absence of multiscale observations, remain speculative.

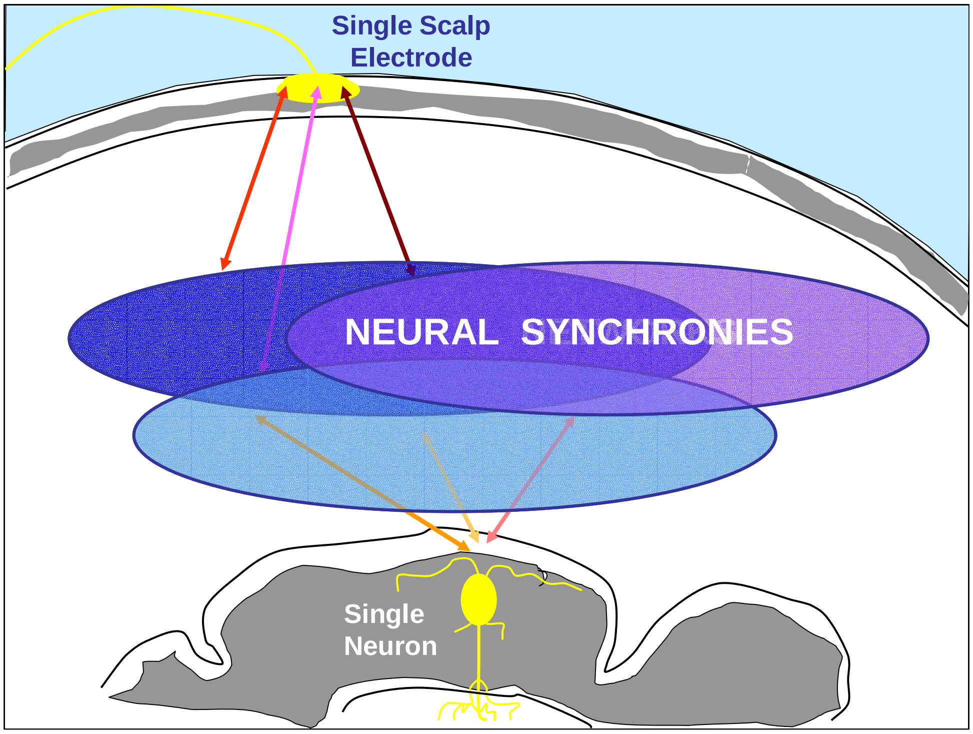


There has been little direct recording and analysis of distributed event-related dynamics in cortex. Here, a distributed coherence event was described by Klopp et al. in intra-cortical data recorded pre-surgically from epileptic patients, beginning 150 ms after presentation of a visual (face) stimulus.



S Makeig, A Delorme, M Westerfield, J Townsend, E Courchesne, TJ Sejnowski, *PLOS Biology* (2004)

Distributed neural dynamic events may also be observed in scalp-recorded data. Here, following a speeded button press in a visual spatial selective attention experiment, subject button presses are following by a transient theta band coherence event (Makeig et al., *PLOS Biology*, June 2004).



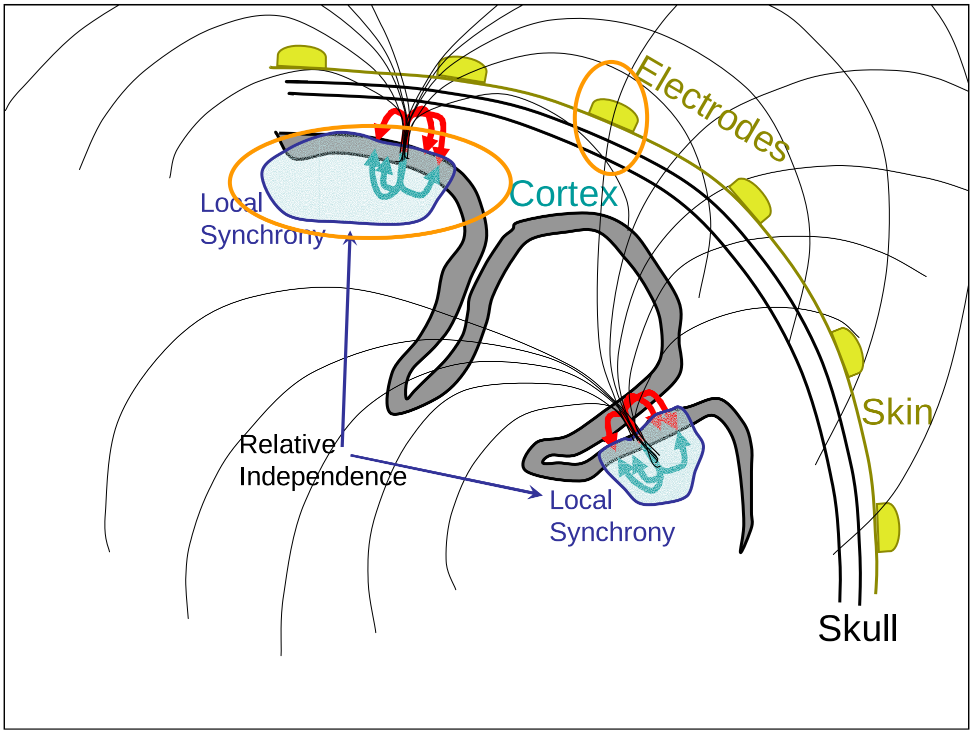
Do single neuron spike recordings say more about brain function than scalp EEG recordings?

Why record scalp EEG or MEG data to understand neurophysiology, if the ‘active’ part of the brain is its neurons?

From a logical point of view, a single neuron can be said to be as ‘far’ from the brain as a single scalp electrode – not physically, of course, but logically. How?

Spiking neurons fire only when they receive sufficient synchronous input (modulated by the correct threshold conditions, etc). A single neuron may respond to many spatially distinct input volleys.

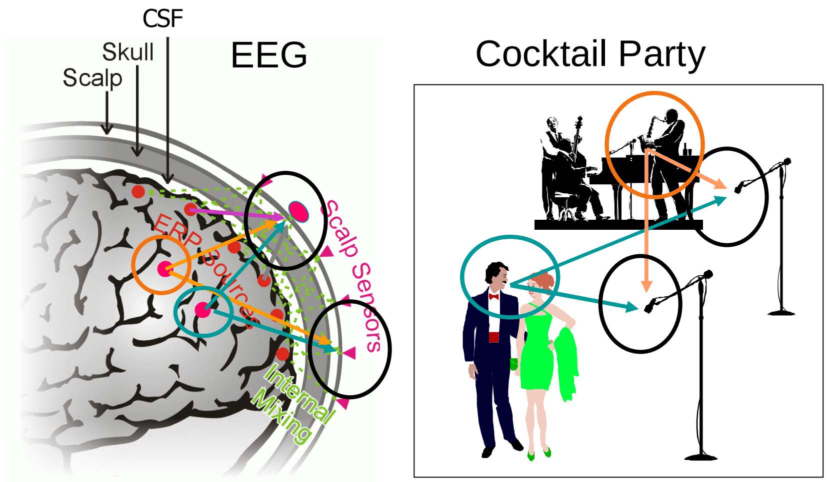
Similarly, a single scalp electrode (pair) typically picks up the sum of activities of macroscopic electrical synchronies arising in many parts of cortex.



Synchronous activity within an oriented patch of cortical neuropile projects to most of the scalp. This creates an unmixing or **source separation** problem – which comes, in logical order, before the question of inverse source localization.

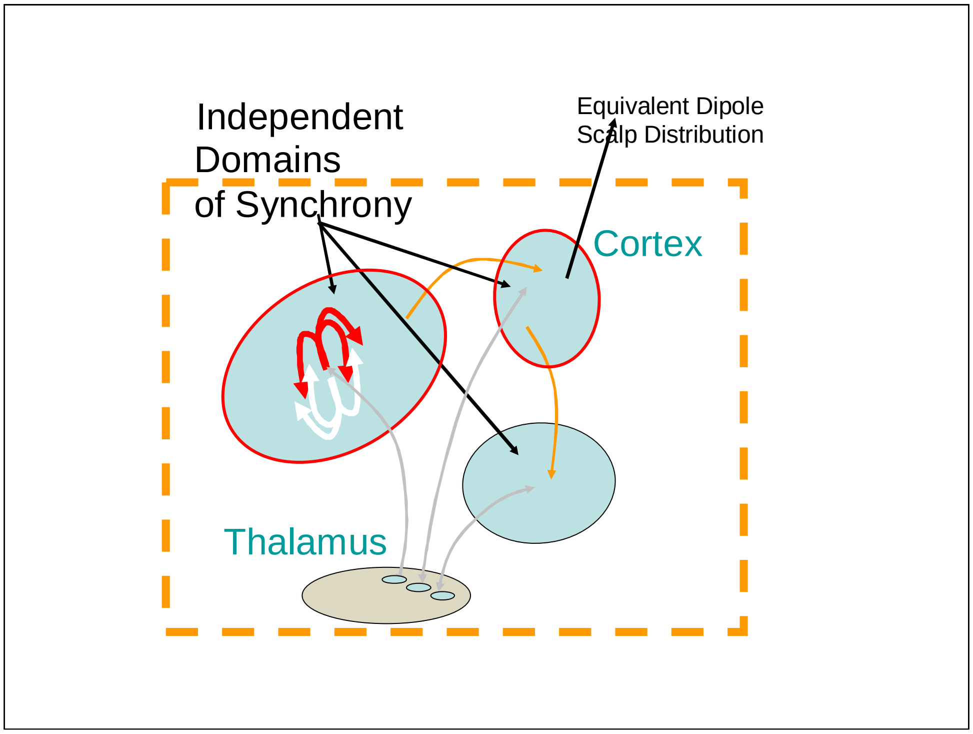
(Note: fields shown here as exiting the scalp would be accurately depicted in this cartoon only if the subject were immersed in a salt bath!).

Blind EEG Source Separation by ICA



Independent Component Analysis (ICA) (right) can be used to separate N sound sources summed in recordings at N microphones, without relying on a detailed phonological model of the sounds characteristics of each source – this is so-called “blind separation.” ICA uses the presumption that the waveforms of the individual sound sources are independent over time.

Applied to EEG data (left), ICA assumes that the EEG is predominantly composed of a number of domains of synchronous neural (or neuroglial) activity, each of which must, by simple biophysics, project to most of the recording scalp electrodes. If synchronous activity within these domains are predominantly independent of each other, ICA can separate the summed signals from these domains into records of their separation activities, given that the number of such domains making large contributions to the recorded signals are smaller than the number of recording sites.



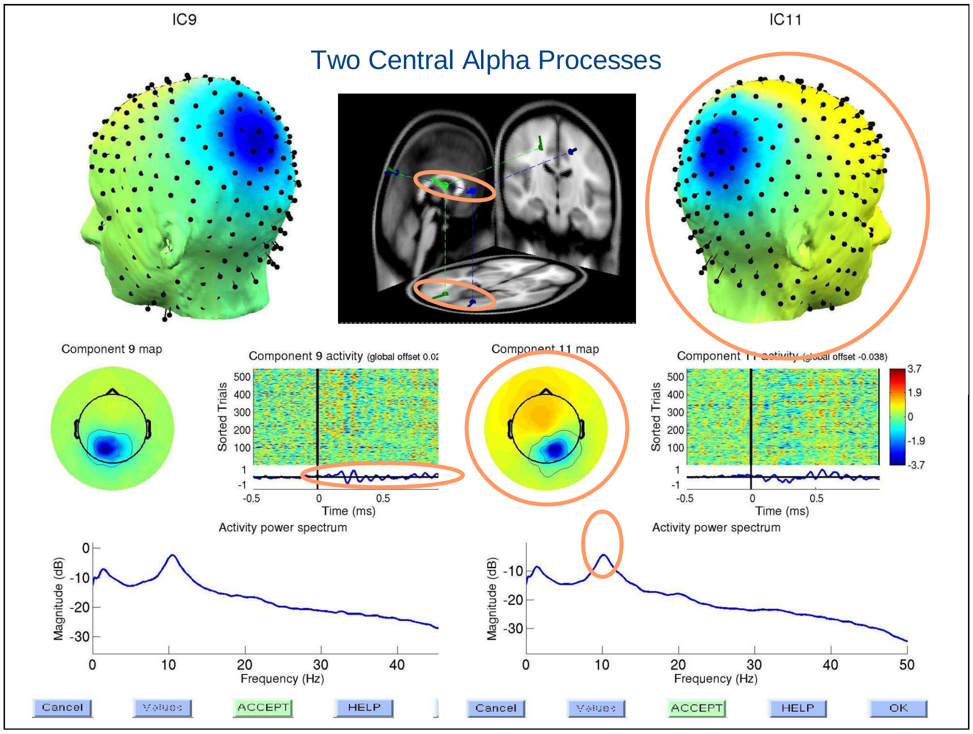
The concept that the activities (across sufficient time) in different partially-synchronized cortical patches may be roughly **independent** of each other is supported by a simple biophysical argument.

Within neuropile, lateral coupling is extremely weighted towards short-range interactions – particularly for inhibitory cells, which form a vital part of circuits producing and maintaining oscillatory activity.

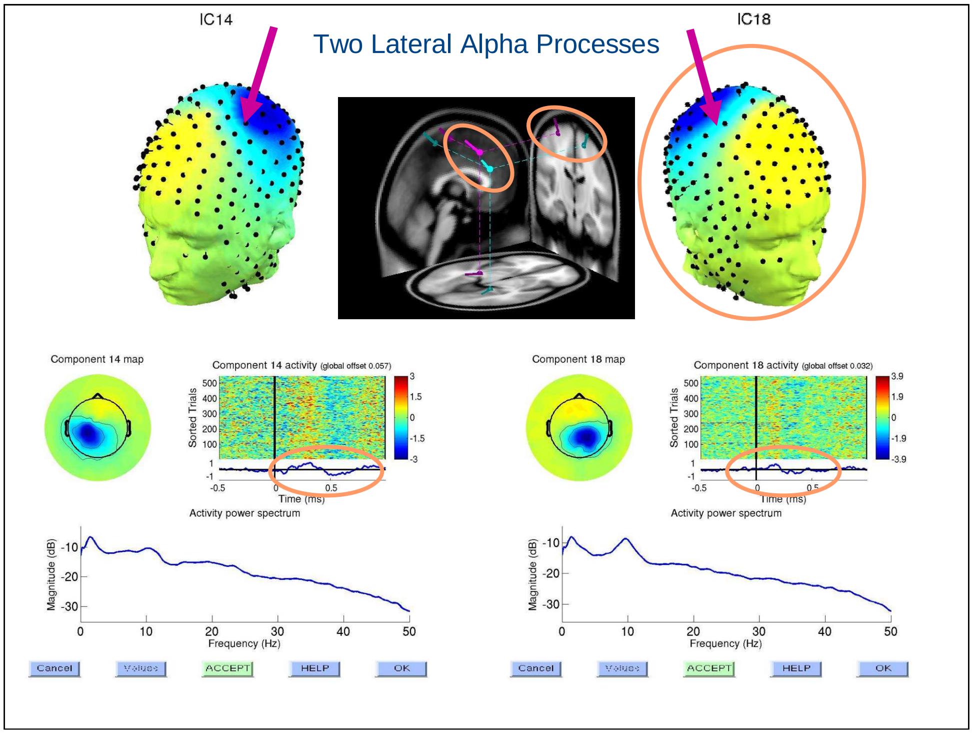
This means that partial synchrony should spread outwards from foci – like Freeman's pond ripples – and remain continuous and compact out to some limit of support.

Also, thalamocortical coupling, also important for generating and maintaining cortical oscillatory activity, is primarily radial.

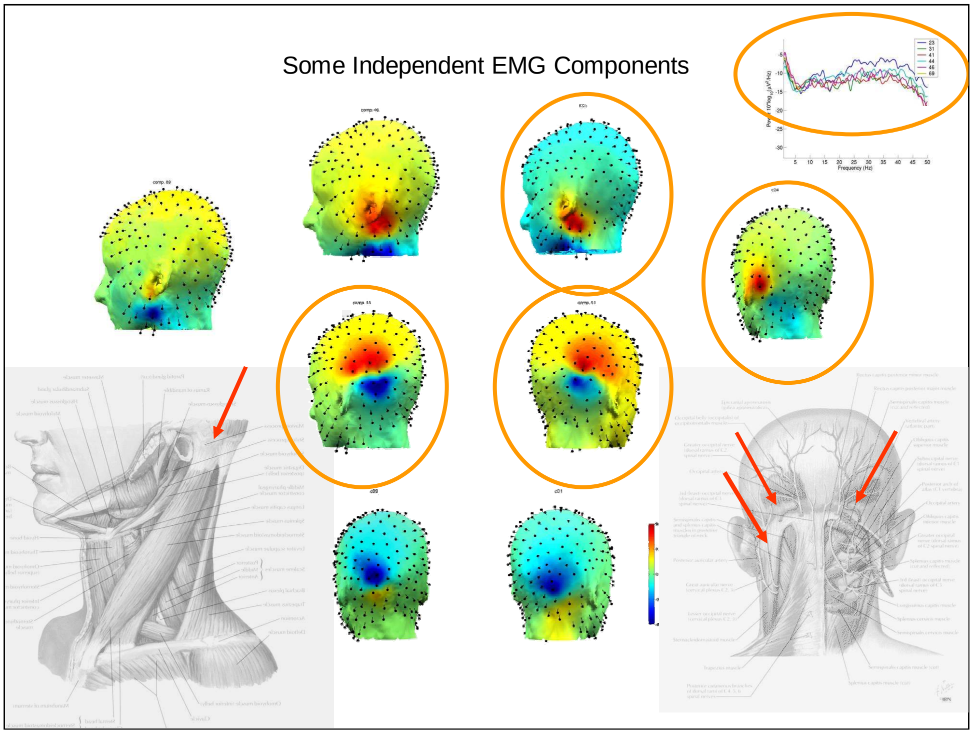
Both these factors should allow quasi-independent patches of oscillatory or more complex dynamics to occur in different cortical patches – in line with the assumptions of ICA applied to EEG or MEG scalp signals.



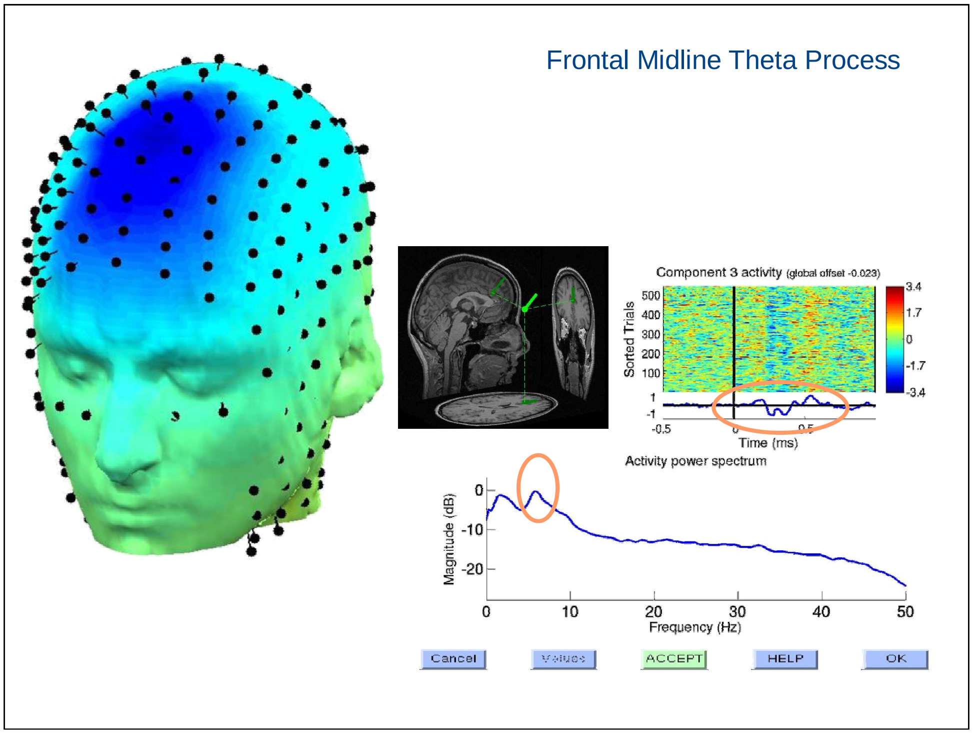
ICA decomposition of a recent 256-channel recording of a subject performing a visual spatial selective attention task produced about 30 maximally independent component processes with distinct dynamics and scalp projection maps strongly resembling an equivalent current dipole – a signature of synchronized activity within a connected cortical patch. Two such processes are shown here.



Two more such independent processes from the same session.



Some of the many single-muscle (EMG) processes separated from the same session recordings …



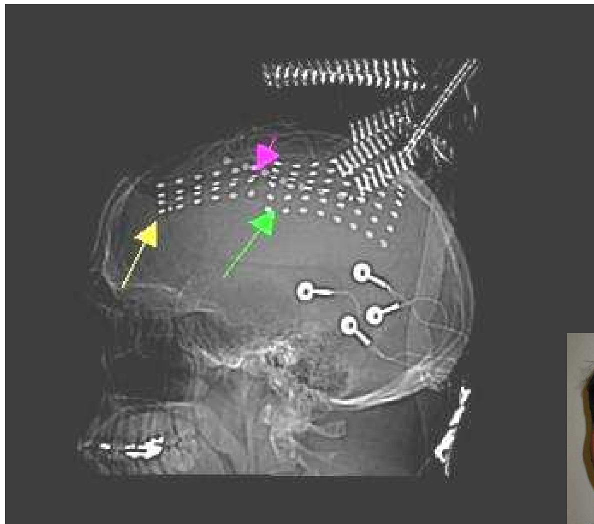
Another process isolated by ICA from the same task session captures the well-known frontal midline theta (fm-theta) rhythm associated with concentration.

Scales of Synchrony

- The lateral extent of partial synchrony involved in processes appearing on the scalp as independent EEG components is unknown.
- Human multiscale recordings are possible.

At the Swartz Center, UCSD, we are beginning a project to record simultaneous high-density EEG and cortical grid data from epileptic patients undergoing pre-surgical monitoring, in collaboration with Dr. Greg Worrell of the Mayo Clinic, Rochester MI.

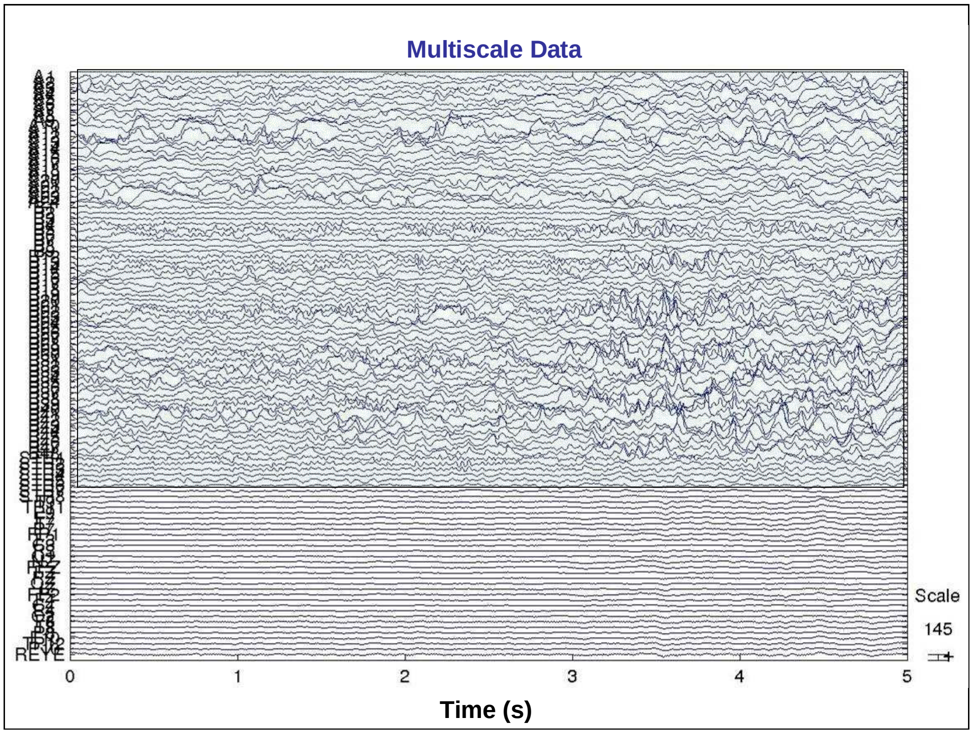
Human Multiscale Recordings



Dr. Greg Worrell, Mayo Clinic, Rochester MN

Dr. Il Keun Lee, SCCN / INC / UCSD

Scott Makeig and Il Keun Lee, MD, a clinical research fellow at SCCN, are working with Dr. Worrell to collect and analyze these data. Here, grids and strips are implanted in a patient and record cortical field activities while 32 scalp electrodes (4 shown). record EEG activities.



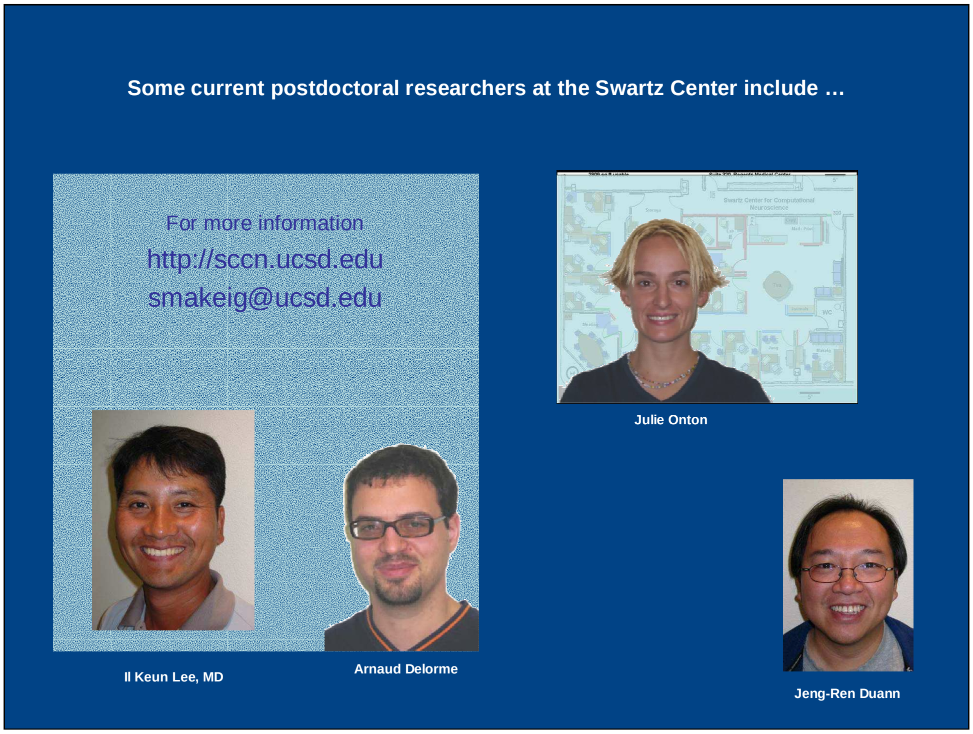
Five seconds of concurrent cortical grid (top) and EEG (bottom) activity. The EEG signals are 6 times smaller than the grid-recorded (ECOG) activity.

Multiscale Brain Communication

- Biasing of spike synchrony by extracellular field potentials may occur at different spatial scales, with different effects.

The spatial scale(s) of partial synchrony giving rise to scalp-recorded fields are not known, but may be extracted from multiscale recordings.

We believe sufficient analysis of multiscale brain data can reveal inherent features of brain dynamics that may not be observable in data collecting at a single spatial scale.



Inquiries are welcome…

Scott Makeig
June 6, 2004