RAIN Brains:
Mammalian Neocortex as a Hybrid Analog-Digital Computer

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ABSTRACT

What kind of computer is the mammalian brain? To improve upon simple rate-based artificial neural networks, computational neuroscience research over the past decade focused on more biologically realistic spiking neuron models—but still ascribing, on the millisecond time scale, a ***digital*** overtone to brain processing. A more recent development has been to explore the spectral properties of subthreshold membrane potentials, emphasizing an ***analog*** mode of computing. Together, by modeling the fine temporal structure of neural signals, these trends have revealed a great diversity of collective ***spatiotemporal regimes***: synchronization & phase locking, correlations & traveling waves, rhythms & chaos, etc. Through recurrent (and plastic) synaptic connections, neural cells transiently interact as ***dynamical subnetworks*** that promise an immense richness of coding expression and computational power, combining the discrete and the continuous. → 1. TEMPORAL & ANALOG CODE

What repertoire of dynamical regimes ("phase diagrams") can such subnetworks sustain? In the classical feedforward view, subnetworks (layers, cell assemblies) are initially mostly silent and have to be literally activated by an input or a "lower" area. Our work subscribes to a new paradigm, in which subnetworks already possess viable and complex endogenous activity modes that are only ***perturbed*** through coupling with an input or other subnetworks. Using spiking neural simulations, we describe here progress to-date towards building cohesive "analog-digital perturbation" principles that can underlie biological attention, pattern recognition, short- and long-term memory, and motor responsiveness to natural environmental stimuli. → 2. MESOCIRCUITS In particular:

- We describe the performance and sensitivity of dynamically igniting-and-quenching ***R***ecurrent ***A***synchronous ***I***rregular ***N***etworks (RAINs). We explore the regimes and phase transitions of RAINs under conditions of calibrated voltage-sensitive ionic membrane channels, synaptic facilitation and depression, and Hebbian spike-timing dependent plasticity (STDP). Specifically, we demonstrate the spontaneous emergence of alternating sub-100ms states of subthreshold (i.e., analog) correlation-decorrelation, suggesting a natural mechanism of intrinsic clocking. → 3. RAIN NETWORKS
- We also study "lock and key" properties of RAIN activation, i.e., a model of pattern recognition and nondiscrete memory storage based on a dynamics of ***coherence induction*** triggered by input stimuli (the "keys"). Here, learning a pattern (a "lock") means tuning synaptic efficacies to a point of maximal postsynaptic response. → 4. LOCK & KEY
- Finally, we discuss the importance of embodied social robotics to "teach" intelligent behavior to RAIN brains, and speculate on the instantiation of RAIN brains in compact analog VLSI architectures. → 5. ROBOT SENTRY

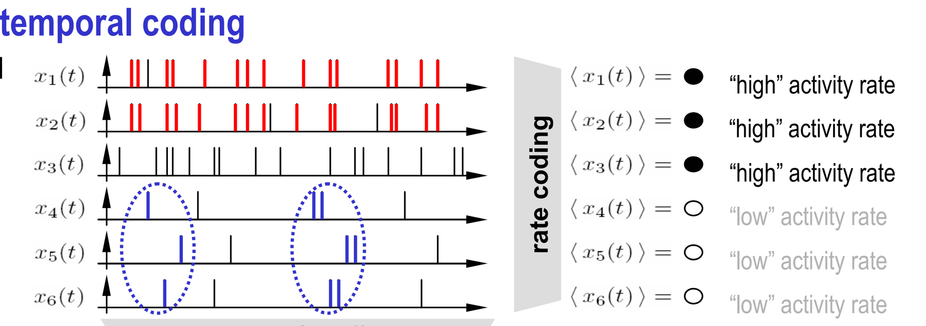
1. TEMPORAL & ANALOG CODE

Rate coding vs. temporal coding

there is more to neural signals than mean activity rates

→ look at ***temporal correlations*** among spikes

- synchrony (zero delay)
- rhythms (nonzero delays)

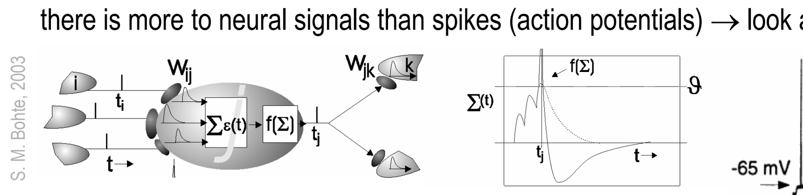


$\langle x_1(t)\, x_2(t) \rangle \gg \langle x_1(t)\, x_3(t) \rangle$ ➢ 1 and 2 more in sync than 1 and 3

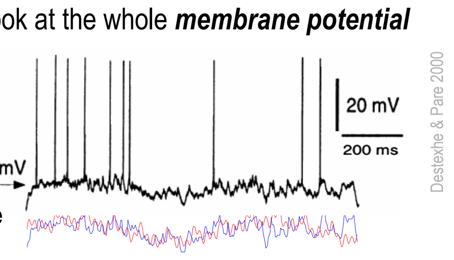
$\langle x_4(t)\, x_5(t-\tau_{45})\, x_6(t-\tau_{46}) \rangle$ ➢ 4, 5 and 6 correlated through delays

Digital-temporal vs. analog-temporal coding

there is more to neural signals than spikes (action potentials) → look at the whole ***membrane potential***



neurons receive a great amount of ***background activity*** from close or remote cortical areas; this activity is ***irregular*** but somewhat ***rhythmic*** and has a critical influence on the neurons' ***responsiveness*** → this suggests a new form of ***analog binding***, instead of spike synchrony



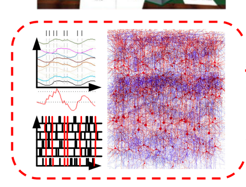
$.55\sin(1.7(2\pi t)) + .25\sin(12.2(2\pi t)) + .2\sin(24(2\pi t)) + .25\sin(50(2\pi t))$

2. MESOCIRCUITS

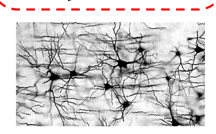
Mesocircuits: the missing link between neural nets and AI

- ✓ at the macroscopic level: AI = symbols, syntax, production rules
  logical systems define high-level ***symbols*** that can be ***composed*** in a generative way; however, they are lacking a "microstructure" needed to explain the fuzzy complexity of perception, categorization, motor control, learning
- ✓ at the microscopic level: neural networks = neurons, synapses, activation rules
  in neurally inspired dynamical systems, network ***nodes*** are ***activated*** by association; however, they are lacking a "macrostructure" needed to explain the systematic compositionality of language, reasoning, cognition
- → need for a **"mesoscopic"** level, populated with spatiotemporal patterns (STPs)
  STPs are complex dynamic cell assemblies supported by ordered connectivity, for ex.: synfire chains, polychronous groups, cortical columns, analog keys & locks, etc.

macrolevel: Artificial Intelligence



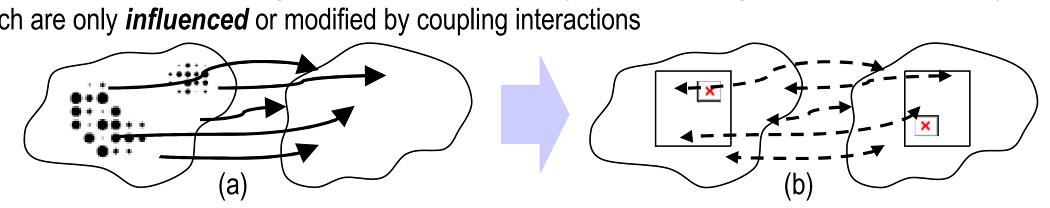
mesolevel: Complex Neural Systems



microlevel: Neural Networks

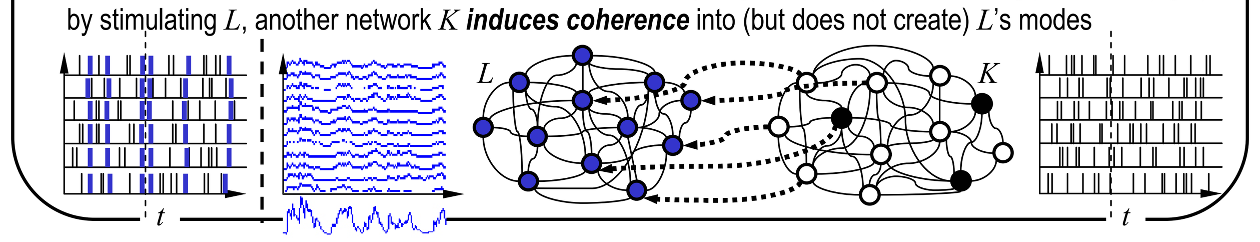
New neural dynamics: perturbation by coupling

(a) old "input/output" paradigm → a lower area literally ***activates*** a higher area, initially silent
(b) new "perturbation" paradigm → subnetworks already possess endogenous modes of activity, which are only ***influenced*** or modified by coupling interactions

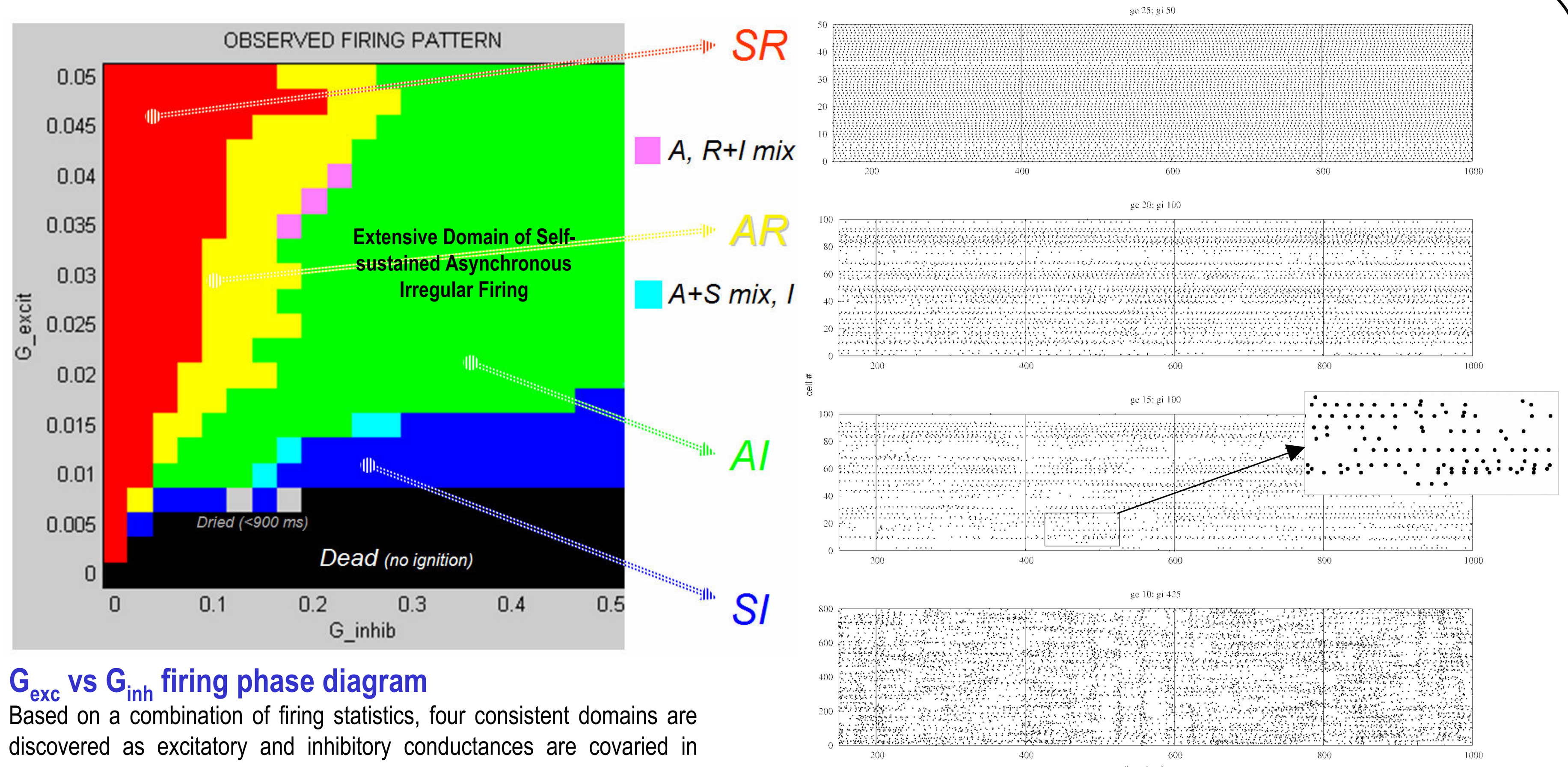


Digital or analog coherence induction through coupling

a subnetwork L has mixed ***endogenous modes*** of activity, digital spikes (left) or analog potentials (right): by stimulating L, another network K ***induces coherence*** into (but does not create) L's modes

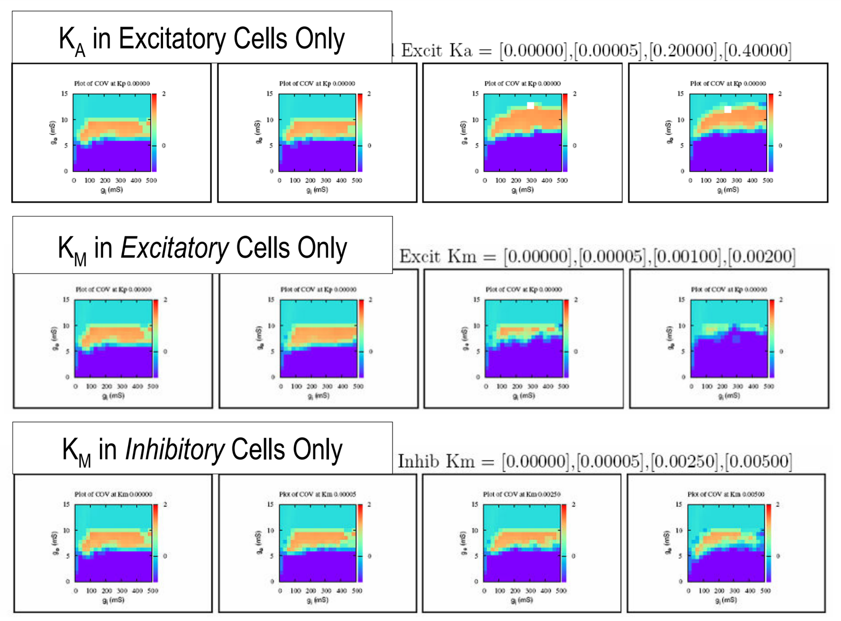


3. RAIN NETWORKS



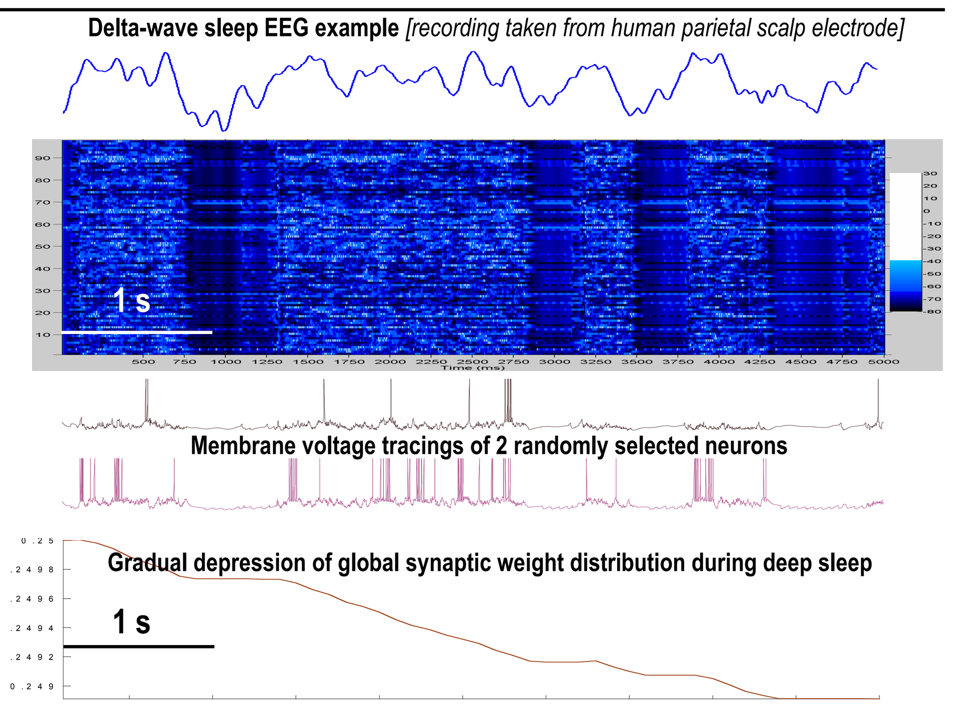
G_{exc} vs G_{inh} firing phase diagram

Based on a combination of firing statistics, four consistent domains are discovered as excitatory and inhibitory conductances are covaried in separate experiments.



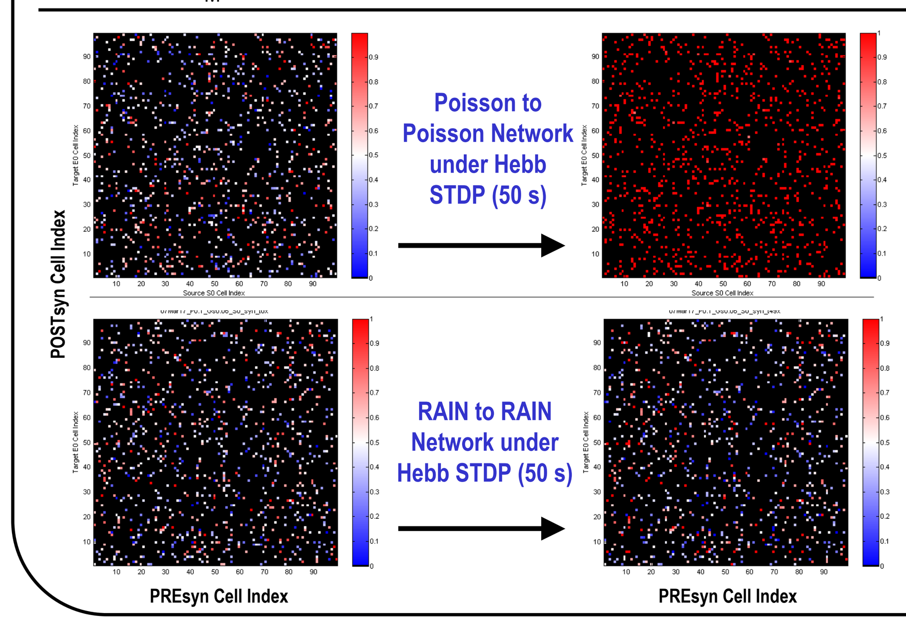
Effect of potassium channels on RAIN domain

Different classes of membrane ion channels differentially alter the dynamics of the RAIN network (upper row: increasing K_A channels in excitatory cells; middle row: increasing K_M in excitatory cells; lower row: increasing K_M in inhibitory cells only).



Sleep emulation

Cyclic depression with active Hebbian synapses results in gradual depression of all synaptic weights (c/w renormalization of Tononi & Cirelli, *Sleep Med Rev 2006*).



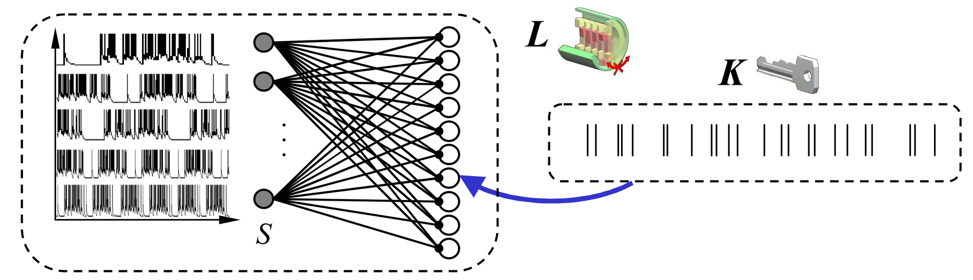
Catastrophic Hebbian STDP prevented by RAIN

Redistribution of synaptic weights among 4000 neurons. A small generator network of 100 neurons fires either with Poisson or RAIN patterns (at identical mean frequencies). This generator network connects with 0.1 probability to a 4000-cell network, of either [upper] disconnected discrete cells forced to fire in a Poisson pattern, or [lower] a fully interconnected RAIN. +Hebb is favored slightly under our STDP settings. Note that all weights shift rapidly from the mean (0.50 +/- 0.25) toward the maximum under Poisson stimulation conditions [top right], whereas synaptic weights redistribute asymptotically to intermediate lower or higher values under RAIN conditions. Black pixels represented unconnected synapses; minimal change occurs beyond 50 seconds.

4. "LOCK & KEY" COHERENCE INDUCTION

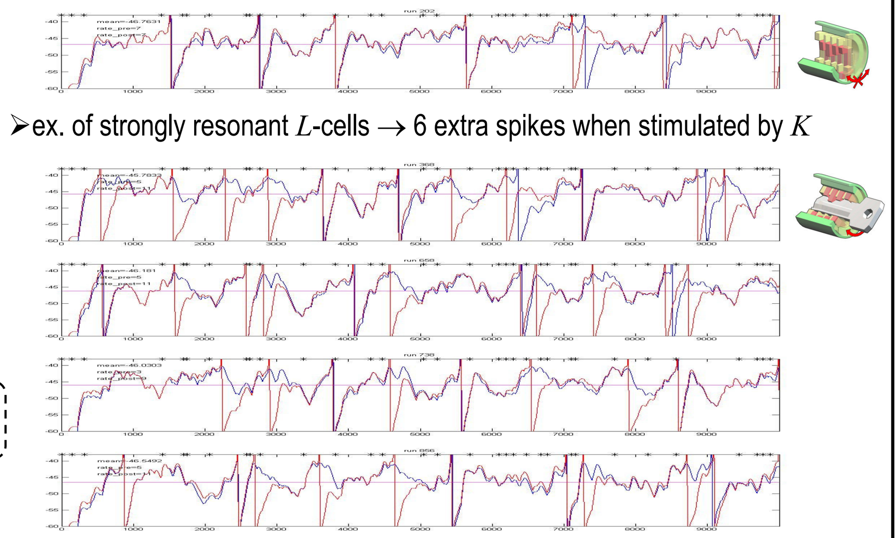
Preliminary study with small lock & key networks

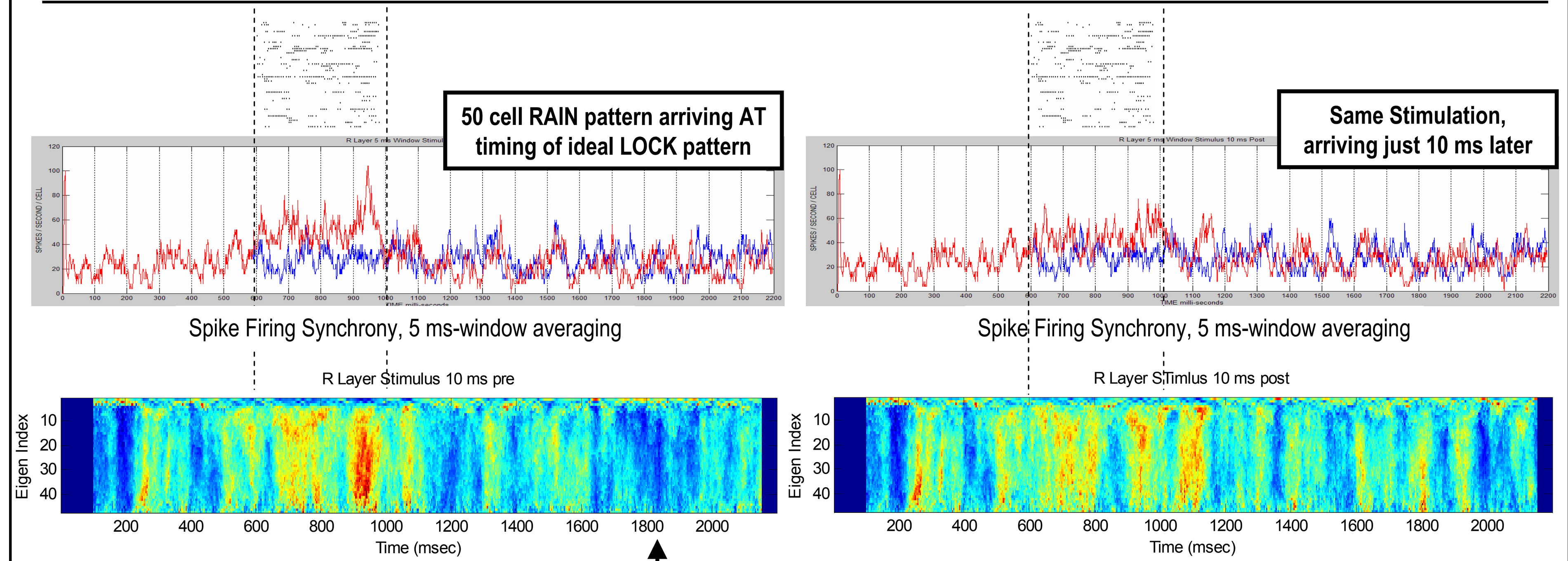
- ✓ **lock network L** contains 100 integrate-&-fire neurons that receive input from 20 background source cells S through different combinations of synaptic weights; S cells are bursting at various frequencies f and burst timings (phases) φ; this creates in L-cells complex subthreshold membrane potential landscapes $\{V_i(t)\}_{i=1\ldots n}$, generally at a low or zero spiking frequency
- ✓ **key K** is a random train of spikes; when L is stimulated by K, the firing rates of the L's cells ***increase more or less*** depending on the match between the spectral composition of the cells' potentials V_i's and the temporal structure of K



➢ example of nonresonant L-cell (blue signal = intrinsic potential; red signal = potential when excited by K) → 0 extra spikes

➢ ex. of strongly resonant L-cells → 6 extra spikes when stimulated by K

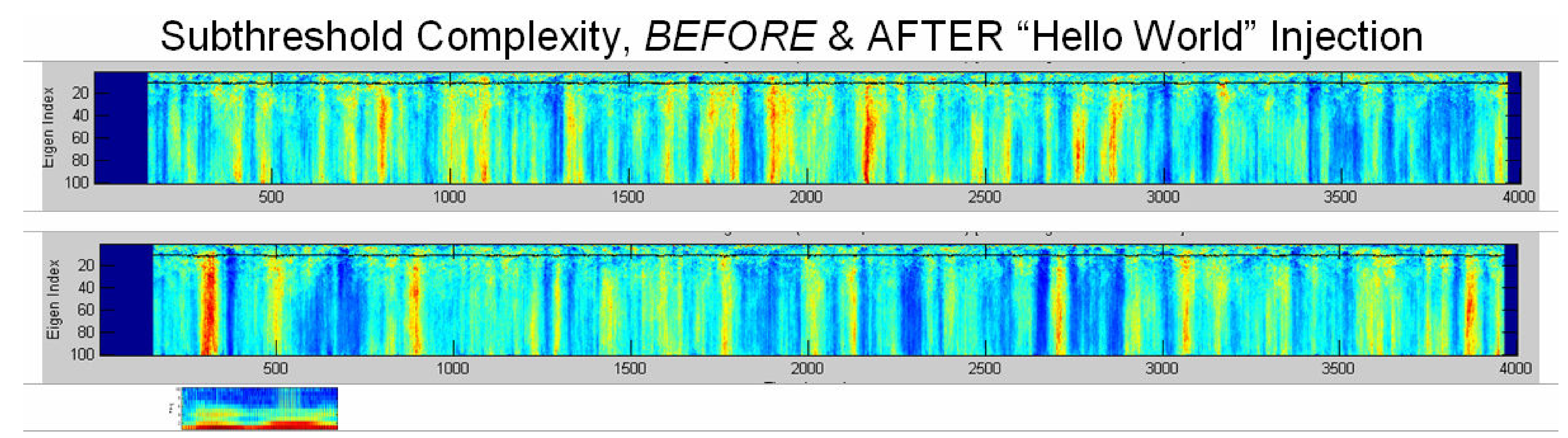




"Lock & key" resonance of interacting RAIN Networks

[upper panel] A 400-ms pattern [between dashed lines] of firing was recorded from a 4000-cell RAIN network; an identically timed pattern of pulses was used to activate 50 cells 5 ms before (left) versus 5 ms after (right) the spike timing which would otherwise have occurred. Significantly more synchronous & mean firing is observed on the left.

[lower panel] Subthreshold EIGENVALUE distribution shows enhanced complexity [between dashed lines] with LOCK & KEY timing (left), with rebound low complexity beginning about 1650 ms (650 ms after end of external stimulation [arrow]).



Spontaneously alternating RAIN subthreshold correlation structure & coherence due to transient perturbation

4 seconds of a 4000-cell RAIN network, before (upper) and after (lower panel) injection of only 10 cells with a spiking spectral (10 frequency) representation of 2 words (in the 200-700 ms window). Note irregular, spontaneous 25-100 ms alternations of complexity, and effect of sound during and after injection. Black line separates absolute eigenvalues above and below a value of 1.

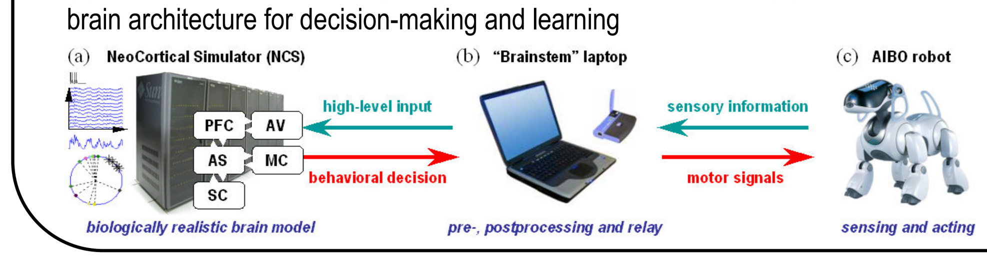
5. ROBOT SENTRY

Cluster-robot loop

original attempt to implement a complete information processing loop between a neural network simulator and a robot, in real time

(c) Robot, e.g., Sony AIBO or Breazeal's Mobile/Dexterous/Social (MDS) as a sentry or industrial assistant interacts with humans via sensors and actuators

(a) NeoCortical Simulator (NCS) runs on a computer cluster (a); it contains the brain architecture for decision-making and learning



Overview of the brain architecture

simplified model brain: comprises interconnected auditory/visual, associative and motor cortical areas, possibly modulated by prefrontal cortex and subcortical structures

cortical area modeling: spiking neural networks in various dynamical regimes: coherence induction, winner-take-all, persistent activity (bistability), etc., under Hebbian synaptic redistribution

planned functional systems: multimodal processing, working memory, and executive behavior, with attentional and reward signals from subcortical networks

approach: develop different areas independently as modules, then combine them to obtain a global stimulus-response learning

Robot's visual input

coarse Gabor filters transduced into raster of spikes

Visual cortex (VC)

the "key"

Association area (AS)

the RAIN "lock"

Motor cortex (MC)

decision by winner-take-all

Robot's behavioral output

raster of spikes transduced into stereotyped behavior