Criticality as a signature of healthy neural systems

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Neuronal avalanches

Beggs & Plenz (J. Neuroscience 2003) have measured spontaneous local field potentials continuously using a 60 channel multielectrode array in mature organotypic cultures of rat cortex. They have shown that spontaneous activity has an avalanche mode:

- Several avalanches (active electrodes) of all size per hour
- Activity initiated at one electrode may spread later to other electrodes in a not necessarily contiguous manner
- Avalanche size distribution is a power law with an exponent close to -3/2
- Avalanche duration distribution is a power law with an exponent close to -2.0

Universality class: Mean field branching model
Avalanche activity found also in dissociated rat cortical neurons (V. Pasquale et al, Neuroscience 2008)

- Neuronal avalanche behavior depends on time scale of observation
- Neuronal cultures developing in vitro organize differently and exhibit different dynamic state (critical, subcritical, supercritical)
- Critical behaviour depends on the interplay between spiking and bursting activity

Similar scaling behavior found for dissociated rat hippocampal neurons and leech ganglia (A. Mazzoni et al PLoS ONE 2007)
Behaviour at large scale

MEG measurements on humans
(124 patients)

Shriki et al (J. Neurosci. 2013)
Size distribution of activity
Cascades scales with exponent \(-1.5\)
for a critical branching process
Scale-free Brain Functional Network

Eguiluz, Chialvo, Cecchi, Baliki, and Apkarian (PRL 2005) measured by MRI the functionality network in humans performing different tasks.

- Correlation coefficient between magnetic resonance activity in any pair of voxels, $r(x_1, x_2)$ averaged over time.

- Two voxels are functionally correlated if $r(x_1, x_2) > r_c$.
Functional brain network in humans is highly modular (Gallos et al. PNAS 2012)

- Self-similar modules of strong links & Weaker links make it a small world
- Modules with scale-free connections: $P(k) \sim k^{-\gamma}$, $\gamma = 2.1 \pm 0.1$
- 8% synaptic connections between modules
- Strength of intra-module synapses > Strength of inter-module synapses
- Inter-module synaptic connections are established between low connectivity neurons: $P(k_1, k_2) \sim k_1^{-\gamma+1} k_2^{-\epsilon}$, $\epsilon = 2.1 \pm 0.1$
Role of Inhibitory Synapses

About 20-30% inhibitory synapses in mammals (GABA-immunostaining measurements in rat hippocampus (Gulyás AI et al. J. Neurosci. 1999)

Are hubs present in neuronal assemblies? (Bonifazi P. et al. Science 2009)

• Measurements of temporal correlations of calcium activity in hippocampal slices of knockin rats and mice ➔ functional hubs exist

• Perturbation of a single hub triggers the entire network dynamics
• By GFP measurements functional hubs are GABAergic interneurons
We introduce the main ingredients of neural activity:

Threshold firing, Neuron refractory period, Activity dependent synaptic plasticity

- We assign to each neuron a potential $v_i$ and to each synapse a strength $g_{ij}$
- A neuron fires when the potential is at or above threshold $v_{\text{max}}$ (-55mV)
- Neurons can be excitatory or inhibitory
- After firing a neuron is set to zero resting potential (-70mV) and remains quiescent for one time step (refractory period)
- Activity dependent long-term (Hebbian) plasticity and pruning

$$g_{ij}(t+1) = g_{ij}(t) + \alpha \left( v_j(t+1) - v_j(t) \right) / v_{\text{max}}$$

$$g_{ij}(t+1) = g_{ij}(t) - < \delta g_+ >$$

Activity is triggered by random stimulation of a single neuron.

$LdA,CPC, HJH, PRL 2006, PRE 2007$
After training the network by plastic adaptation, we apply a sequence of stimuli at random to trigger avalanche activity.

- different $\alpha$
- regular, small world, scale-free networks
- excitatory and inhibitory synapses

$1.5 \pm 0.1$ & $2.1 \pm 0.1$ for avalanche size & duration

Millmann, Mihalas, Kirkwood, Niebur, Nat Phys 2010

ORIGIN OF THE SCALING BEHAVIOR

Critical scaling \( \sigma = 1 \) \( \frac{1.28 \text{ (Zhang model)}}{} \) for no plasticity

Resilience to damage

(with plasticity and refractory time)

\[ 1.5 \pm 0.1 \]


(Katifori e al PRL 2010; Corson PRL 2010)
Resilience to damage
Power spectra of spontaneous neuronal activity

Lombardi et al, Chaos 2017

- EEG exponent varies $\beta \in [0.9, 1.3]$ with frequency range, exp. condition, brain regions (Pritchard 1992, Freeman et al 2000)
- EEG-MEG in temporal and frontal areas $\beta \approx 2$
  whereas in midline channels $1/f$ (Dehghani et al 2010)
- Spectrum $1/f^\beta$ for $\alpha$ oscillations in EEG and MEG data with smaller exponent (Linkenkaer-Hansen et al 2001)
- $1/f$ spectrum of fMRI signal (He et al 2014), $\beta \approx 2$ for epileptic patients

Numerically the EEG signal from a neuronal network is the sum of potential variations occurring at all neurons at each time step.
• Power law regime in a frequency range 1-100Hz
• Low frequency cutoff towards white noise avalanche durations $T$ in the exponential cutoff of $P(T)$
• Exponent $\beta \approx 2$ (brown noise) for purely excitatory networks

$\beta \rightarrow 1$ for $p_{in} \rightarrow 30\%$

Balance of excitation and inhibition controls long-range temporal correlations
Experimental avalanche inter-time distribution

Experiments by D. Plenz on coronal slices from rat dorsolateral cortex (Lombardi et al PRL 2012)

- Initial power law regime with exponent $2.15 \pm 0.32$
- Minimum at about $\Delta t \approx 200\text{ms}$
- Maximum at about $\Delta t \approx 1 - 2s$
Up-states and down-states

- Spontaneous neuronal activity can exhibit slow oscillations between bursty periods, or **up-states**, and quiet periods, called **down-states**.
- **Down-states** due to a decrease in the neurotransmitter release (exhaustion of available synaptic vesicles or increase of a factor inhibiting the release, as nucleoside adenosine), the blockade of receptor channels by the presence of external magnesium, spike adaptation...
  “Down-state of the network is a state of mutually-enforced quiet”
- Network properties explain the **up-state**: Any input may trigger some mutual excitation and the network will re-excite itself to the up-state
- Avalanches are critical in the up-state and subcritical in the down-state (Millman et al Nat Phys 2010)
- The alternation between US and DS is expression of the balance between excitation and inhibition

Neuron state:
Neurons toggle between two preferred membrane potentials: a hyper-polarized one in the down state, and a more positive, depolarized one, in the up-state.
Implementation of up and down states

- **Down-state**
  - After an avalanche with \( S \geq S_{\text{min}} \), all neurons active in the last avalanche become hyperpolarized depending on their own activity.
  - \( h > 0 \) is a hyper-polarization constant
  - \( v_i = v_i - h \delta v_i \)
  - Short term memory at neuron level
  - System is stimulated by a small constant random drive

- **Up-state**
  - After an avalanche with \( S < S_{\text{min}} \), all neurons active in the last avalanche become depolarized depending on the last avalanche size.
  - \( v_i = v_{\text{max}} \left( 1 - \frac{s}{S_{\text{min}}} \right) \)
  - the smaller the last avalanche, the closer the potential to the firing threshold
  - Memory at the network level
  - System is stimulated by a random drive (network effect which sustains the up-state) \( \in ]0, \frac{S_{\text{min}}}{S}[ \)
Spontaneous neuronal activity exhibits slow oscillations between up-states, and down-states.

Small correlated avalanches, neurons depolarized after firing.

Disfacilitation period after large avalanches, neurons hyperpolarized after firing.

Balance between excitation and inhibition.

Homeostatic regulatory mechanism.
expressing the balance between excitation and inhibition is the unique parameter controlling the distribution

$R = h / s_{\text{min}}$

simple dual drive does not work!

Homeostatic regulatory mechanism
Critical vs. supercritical systems
# Brainwaves, Frequencies and Functions

<table>
<thead>
<tr>
<th>Unconscious</th>
<th>Conscious</th>
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<tbody>
<tr>
<td>Delta</td>
<td>Beta</td>
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<tr>
<td>0.5 – 4 Hz</td>
<td>13 – 30 Hz</td>
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<tr>
<td>Theta</td>
<td>Gamma</td>
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<td>4 – 8 Hz</td>
<td>30-42 Hz</td>
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<td>Alpha</td>
<td>Instinct</td>
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<td>8 – 13 Hz</td>
<td>Emotion</td>
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<td>Conscience</td>
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<td>Will</td>
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<td>Survival</td>
<td>Drives</td>
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<td>Deep sleep</td>
<td>Feelings</td>
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<td>Coma</td>
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<td>Dreams</td>
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<td>Awareness of the body</td>
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<td>Integration of feelings</td>
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<td>Perception</td>
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<td>Concentration</td>
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<td>Mental activity</td>
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<td>Extreme focus</td>
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<td>Energy</td>
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<td>Ecstasy</td>
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- Remove avalanches smaller than a given threshold $s_c$
- Evaluate new $P(\Delta t, s_c)$
- Peaks develop
  - at $\theta$ band (4-15 Hz)
  - at $\gamma$ band (30-100 Hz)
Correlations exist between size and quiet times

No peaks emerge for reshuffled time series
Avalanches and oscillations

- Hierarchical structure corresponding to nested θ-γ oscillations

- Large avalanches occur with θ (4-15 Hz) frequency and trigger smaller ones corresponding to faster γ (30-100 Hz) oscillations

- Sizes related to θ cycles fall within the blue region of P(s)

- Sizes related to γ cycles fall within the green region of P(s)

- The relationship between avalanches and oscillations does not imply a characteristic size

Collaborations

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