Connectivity and synchronization: comparison of neural observations and experiments with toy networks

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Two views on brain organization

Functional specialisation:
What regions respond to a particular experimental input?

Image source: Sporns 2007, SPM Course
Two views on brain organization

Functional specialisation:
What regions respond to a particular experimental input?

Functional integration:
How do regions influence each other? How does cognition emerge from interacting regions?

Image source: Sporns 2007, SPM Course
Topography to topology

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Image source: Eileen Kraemer, 2005; Rosazza & Minati, 2011; © Authors and Springer Verlag
Networks are everywhere

<table>
<thead>
<tr>
<th>Network</th>
<th>Nodes</th>
<th>Edges</th>
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</thead>
<tbody>
<tr>
<td>Internet</td>
<td>routers</td>
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<tr>
<td>brain</td>
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<td>synapses</td>
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<td>binding sites</td>
</tr>
<tr>
<td>ecology web</td>
<td>species</td>
<td>competition</td>
</tr>
</tbody>
</table>
Properties of self-organized networks

Small-world-ness:
Properties of self-organized networks

Scale-free-ness:
Three aspects of brain connectivity

- anatomical/structural connectivity
  = presence of axonal connections
Three aspects of brain connectivity

- anatomical/structural connectivity
  = presence of axonal connections
- functional connectivity
  = statistical dependencies between regional time series
Three aspects of brain connectivity

1. anatomical/structural connectivity
   = presence of axonal connections
2. functional connectivity
   = statistical dependencies between regional time series
3. effective connectivity
   = causal (directed) influences between neurons or neuronal populations

Image source: Sporns 2007, SPM Course
Brain connectivity and dynamics

Structural connectivity (i.e. physical links)

Dynamics

Functional connectivity (i.e. synchronization)
Brain connectivity and dynamics

Structural connectivity (i.e. physical links)

Dynamics

Functional connectivity (i.e. synchronization)

Plasticity

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Multiple scales

- **Microscale** ($10^2$-$10^3$ neurons)
  - Cortical (groups of) columns/microcircuits
  - Receptive field tiling, “building blocks” for larger circuits

- **Mesoscale** ($10^5$-$10^7$ neurons)
  - Gyral/sub-gyral circuits
  - Multi-sensory integration, associative functions

- **Macroscale** ($10^9$-$10^{11}$ neurons)
  - Large-scale multi-gyral/bihemispheric circuits
  - Higher cognitive functions, consciousness
Topological and dynamical properties

- **Topology**
  - Modularity
  - Scale-free-ness
  - Small-world-ness

- **Dynamics**
  - Non-linearity
  - Possible chaoticity
  - Criticality
The brain is totally unlike a digital computer

Design vs. Emergence

J. Von Neumann
1903-1957

A. Turing
1912-1954

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Image credit: Wikipedia, others
Is there anything *physically* unique about it?

Seemingly, everywhere one looks, there is a paradox…
Centrality and universality of emergence

Whole (collective behavior) >> Sum of parts (elemental dynamics)
Why compare to other *physical* systems?

e.g. non-linear electronics

Numerical simulation
Why compare to other physical systems?

In non-linear physical systems the emergence of global properties often fundamentally influenced by "nuances" such as:

- Parametric mismatches between constituent elements,
- Electrothermal noise in the oscillatory variables,
- Noise in the dynamical parameters,
- Non-ideal behaviours such as presence of "parasitic" elements,
- Lack of discretization and so on.

Not at all trivial to capture numerically!
Why would chaotic networks be interesting?

A classic example: the double-rod pendulum...

Why would chaotic networks be interesting?

Rapid divergence... but it is not the main point...

\[ x(t) = f^t(x_0) \]

\[ x(t) + \delta x(t) = f^t(x_0 + \delta x_0) \]

\[ ||\delta x(t)|| \approx e^{\lambda t} ||\delta x_0|| \]
Why would chaotic networks be interesting?

Self-organization: paradigmatic case of the Belousov-Zhabotinsky reaction

Image credit: Wikipedia, others
Chaos synchronization

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Complexity in simple transistor circuits
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Image source: Minati et al., CHAOS 2017. © AIP
Complexity in simple transistor circuits

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Emergence of community structure

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Image source: Besseling et al., © Elsevier
Emergence of community structure

Ring structural connectivity as elementary substrate
Emergence of community structure
Emergence of community structure
Emergence of community structure

Amplitude fluctuations loosely resemble EEG...

\[ R_C = 120\Omega \ (NMI=0.14) \]

\[ R_C = 270\Omega \ (NMI=0.09) \]

\[ R_C = 470\Omega \ (NMI=0.07) \]
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Dynamics within and outside hubs

Image source: Minati et al., CHAOS 2015. © AIP
Dynamics within and outside hubs

Cortical hubs seem to yield deterministic, non-linear dynamics

Image source: Minati et al., CHAOS 2015. © AIP
Dynamics within and outside hubs

A “toy model” of high-level brain connectivity

Image source: Minati et al., CHAOS 2015. © AIP
Dynamics within and outside hubs

Selective emergence of slow, high-amplitude fluctuations in hubs

Image source: Minati et al., CHAOS 2015. © AIP
Conclusions

1) Relationship between brain connectivity and dynamics

2) Parallels between emergence in the brain and other physical systems

3) Phase transitions in neurons and chaotic oscillators

4) Brain modularity and cluster synchronization

5) Hubs and dynamics
Thank you for your attention

**References:**
1. Minati L. Experimental dynamical characterization of five autonomous chaotic oscillators with tunable series resistance. CHAOS. 2014; 24(3):033110

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