A model of pattern completion based on the CA3 recurrent synapse

Jose Guzman, Michael Frotscher and Peter Jonas
The neural structure for pattern completion

Synaptic basics of pattern completion

Auto-associative network
An autoassociative network can perform *pattern completion* when it associates the input to the principal cells with their own output (Marr, 1971)

1. Storage
2. Activation
3. Recall

adapted from Amaral *et al.*, 1990
Synaptic bases of pattern completion

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Synaptic bases of pattern completion

1. Macro-connectomics

CA3–CA3 connectivity?

CA3 synapses

DG

CA3

CA1
Synaptic bases of pattern completion

1 Macro-connectomics  CA3–CA3 connectivity?

2 Micro-connectomics  properties of recurrent synapses
Synaptic bases of pattern completion

1. Macro-connectomics: CA3–CA3 connectivity?
2. Micro-connectomics: properties of recurrent synapses
3. How are memories stored? (i.e. plasticity rules)
Macro-connectomics

what is the connectivity between CA3 cells?
Macro-connectomics: on CA3–CA3 connectivity

On CA3 numbers

\[ \sim 40,000 \text{ boutons} \]
- Witter et al., 2007
- Li et al., 1994
- Ishizuka et al., 1990

\[ \sim 330,000 \text{ CA3 cells} \]
- Boss et al., 1987
Macro-connectomics: on CA3–CA3 connectivity

On CA3 numbers

- ~40,000 boutons
  - Witter et al., 2007
  - Li et al., 1994
  - Ishizuka et al., 1990

- ~330,000 CA3 cells
  - Boss et al., 1987

Diagram: Scale bar = 100 μm

Number of CA3 cells (~330,000) and boutons (~40,000) in CA3-CA3 connectivity.
Octuple whole-cell recordings

a) Simultaneous recordings

b) Recording configurations

2 x 4

7 x 8

Cell 1
Cell 2
Cell 3
Cell 4
Cell 5
Cell 6
Cell 7
Cell 8

Connections tested
Connections found
Connection probability (%)

4000
3200
2400
1600
800

15672
145

0.92 %

CA3-CA3 synapses
Guzman, Frotscher and Jonas
Octuple whole-cell recordings

a) Simultaneous recordings

b) Recording configurations

2 x 4

7 x 8

50 μm

CA3-CA3 synapses

Guzman, Frotscher and Jonas

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Motifs of connectivity

a) Simultaneous recordings

b) Motifs of hyperconnectivity

c) Connectivity motifs are representative

- **CA3-CA3 synapses**
  - Guzman, Frotscher and Jonas page 13 of 28
what is the connectivity between CA3 cells?

CA3 neurons use motifs of hyperconnectivity embedded on a sparse network
Micro-connectomics

Properties of the CA3–CA3 synapses
Anatomical identification of synaptic contacts

A  Biocytine labeling

B  Identification under light microscopy
   performed under 60X or 100X/1.4 oil-immersion objectives
   - axon and dendrite belong to functionally connected pairs
   - presence of enlargements at the axon/dendrite.
   - appointments located at a single focal plane.

C  Nucleated patches
   Sather et al., 1992
Micro-connectomics: 1–2 contacts per connection

a) Digital reconstruction

b) Putative synaptic contacts

c) Cable modeling

d) Conductance estimation
Micro-connectomics: low number of functional sites

A)

2mM \([\text{Ca}^{2+}]_o\)

1mM \([\text{Ca}^{2+}]_o\)

B)

1mM \([\text{Ca}^{2+}]_o\)

Time (min)

0 10 20 30 40 50 60

0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0

Peak EPSP (mV)

C)

2mM \([\text{Ca}^{2+}]_o\)

D)

1mM \([\text{Ca}^{2+}]_o\)

0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0

Peak EPSP (mV)
Micro-connectomics: low number of functional sites

A

2mM $[\text{Ca}^{2+}]_o$

1mM $[\text{Ca}^{2+}]_o$

B

1mM $[\text{Ca}^{2+}]_o$

Peak EPSP (mV)

Time (min)

C

2mM $[\text{Ca}^{2+}]_o$

Probability density function

Peak EPSP (mV)

D

Number of release sites

Quantal EPSP (mV)

CV

Quantal EPSC (pA)
EPSPs are small but add efficiently

a) EPSP kinetics

b) Temporal summation

c) Spatial summation

d) Low number of CA3 cells for spiking
Properties of the CA3–CA3 synapses

CA3 synapses exhibit a low number of sites and summation
Towards a quantitative model for pattern completion

Full size (330,000 neurons)
Neurons inactive (0) or active (1)
Excitatory synapses follow a clipped Hebbian rule
Inhibition proportional to global excitation level

\[
h_i(t) = \frac{1}{n} \sum_{j=1}^{n} (W_{ij} \circ J_{ij} \circ P_{ij}) X_j(t),
\]

\[
h_i(t) - \frac{1}{n} g_1 X(t) > g_0
\]

Other assumptions: Connectivity 3%, synaptic CV 1

Storage phase

Apply original pattern

Repeat m times

Hebbian plasticity

Retrieval phase

Test degraded pattern

Repeat several times

Determine overlap between original patterns and final patterns

Determine capacity as number of patterns in which overlap is > 0.5

Marr, 1971; Hopfield, 1982; Bennett et al., 1994
Macroconnectomic features determine network capacity for random patterns

A
Dense, local connectivity
\( r = 1 \)
\( C = 1123 \)

B
Sparse, distributed connectivity
\( r = 0 \)
\( C = 7486 \)

C
\( r = 0.5 \)
\( C = 5700 \)

D
overlap
\( r \) 0 0.2 0.4 0.6 0.8 1

distributed local

0 1

overlap

Capacity 8000 6000 4000 2000 0
Macrocortemantic features improve network capacity for correlated patterns

A

\[ r = 0 \]

\[ C = 3850 \]

B

\[ r = 0.05 \]

\[ C = 6328 \]

C

\[ r = 0.10 \]

\[ C = 7624 \]

D

Capacity

\[ 8000 \]

\[ 6000 \]

\[ 4000 \]

\[ 2000 \]

\[ 0 \]

Overlap

\[ 1 \]

\[ 0 \]

Fully distributed

Fully local
1 Macro-connectomics: combination of sparse and dense connectivity
Summary

1. **Macro-connectomics** combination of sparse and dense connectivity

2. **Micro-connectomics** small number of synapses, but very prone to summation
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Acknowledgments

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