Dynamics and stable states in neuronal circuits of the olfactory system

Rainer Friedrich

Nose  ➔  Olfactory bulb  ⇔  Telencephalic areas

Golgi (1905)
Measurement of neuronal activity patterns

High-resolution optical manipulations

Exhaustive circuit reconstruction (EM)
The olfactory bulb

ORN: Olfactory Receptor Neuron; MC: Mitral Cell, GC: Granule Cell; PGC: Periglomerular Cell
Input activity patterns (zebrafish, amino acids)

- Gly (10 μM)
- Ala
- Ser
- Phe
- Tyr
- Trp
- His
- Asn
- Val
- Ile
- Leu
- Met
- Arg
- Lys
- Glu
- Asp

Friedrich and Korsching, Neuron (1997)
Output activity (mitral cells)

Arg

Met

MC 1
MC 2
MC 3

200 ms

Ala (100 μM)
De-correlation of activity patterns

Tyr

100 ms 300 ms 500 ms 700 ms 900 ms 1100 ms

Population vector

Neuron 1

Neuron n

Mitral cell #

Odor (Met, 10 µM)
De-correlation of activity patterns

200 ms  400 ms  600 ms  800 ms  1400 ms

Reconstruction of electrical activity from Ca$^{2+}$ signal by deconvolution

Temporally deconvolved 2-photon calcium imaging

Odor

2-photon microscope

Cell type marker

Calcium indicator (rhod-2-AM)

Activity

Odor

2-photon microscope

Cell type marker

Calcium indicator (rhod-2 AM)

Activity

Pattern decorrelation by local sparsening

Decorrelation

Channel decorrelation: ➞ „Efficient“ coding
- Minimizes neuron number required for transmission

Pattern decorrelation: ➞ „Informative“ coding
- Facilitates discrimination
- Important for storage by associative networks

Known strategies are:
- adaptive (require prior knowledge and training)
- no obvious neuronal implementation
Decorrelation by recurrent networks: mathematical analysis

**Theorem 1**

Thresholding alone invariably causes decorrelation
Decorrelation by recurrent networks: mathematical analysis

Theorem 1

Thresholding alone invariably causes decorrelation

Theorem 2

Recurrent connectivity amplifies threshold-induced decorrelation
Decorrelation by recurrent networks: mathematical analysis

**Theorem 1**
Thresholding alone invariably causes decorrelation

**Theorem 2**
Recurrent connectivity amplifies threshold-induced decorrelation

**Theorem 3**
Recurrent-enhanced decorrelation increases with:
- Sparse connectivity
- High baseline activity (when „sufficiently coupled“)
Theoretical predictions and simulation results

- Simulation
- Theory

Δcorrelation vs. Fan-in (Sparse to Dense)

Δcorrelation vs. Baseline membrane potential

Martin Wiechert
Forward optical probing of neuronal connectivity in the olfactory bulb

Overall connection probability: 0.0034
Olfactory bulb model:
- Recurrent inhibitory connections
- Reciprocal connectivity
- Topographic connectivity
- Naturalistic inputs
Olfactory bulb model:
- Recurrent inhibitory connections
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Decorrelation

**Sparse circuit:**
Few but strong connections

**Dense circuit:**
Many but weak connections

Martin Wiechert
Recurrent networks act as general pattern decorrelators

Similar inputs  Specialist decorrelator

Expected input

Similar inputs  Specialist decorrelator

General input

Similar inputs  General decorrelator

General input

Pattern decorrelation by recurrent networks is not chaotic
Neuronal representations are discontinuous:

- Decision-making: abrupt switching of neuronal output
- Sensory processing: generalization vs. separation
- ...

Hypothesis: abrupt switching between network states?
Pattern classification: generalization vs. separation

Pattern generalization

Pattern separation
Concentration-invariance of mitral cell response patterns

Jörn Niessing
Concentration-invariance of mitral cell response patterns

Principal component analysis

Population vectors

Neuron 1

Neuron n

MC marker

Lys

$10^{-3} \text{ M}$  $10^{-4} \text{ M}$  $10^{-5} \text{ M}$  $10^{-6} \text{ M}$  $10^{-7} \text{ M}$  Blank  $10^{-5} \text{ M}$

ΔF/F (%)
Concentration-invariance of mitral cell response patterns

Output patterns are largely invariant within a range of concentrations

Jörn Niessing
Odor morphing: similar odors
Odor morphing: similar odors

Jörn Niessing
Odor morphing: similar odors
Odor morphing: discrete transitions

Jörn Niessing
Pattern transitions are mediated by small, coordinated ensembles

All mitral cells:

“Switching” cells (10%) removed:
Discrete pattern classification: summary

- Discretization of coding space
- Noise-tolerance vs resolution
- Sensory filter $\rightarrow$ invariances.
- Coordinated switching of responses in small ensembles.

- Consistent with psychophysics.
- Consistent with attractor networks.