Lempel-Ziv in neuronal Systems

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Overview

- The problem context: the Stoop hypothesis
- The Lempel-Ziv-distance between spike trains
- Neuronal clustering in the olfactory system
- Neuronal firing reliability in the visual system

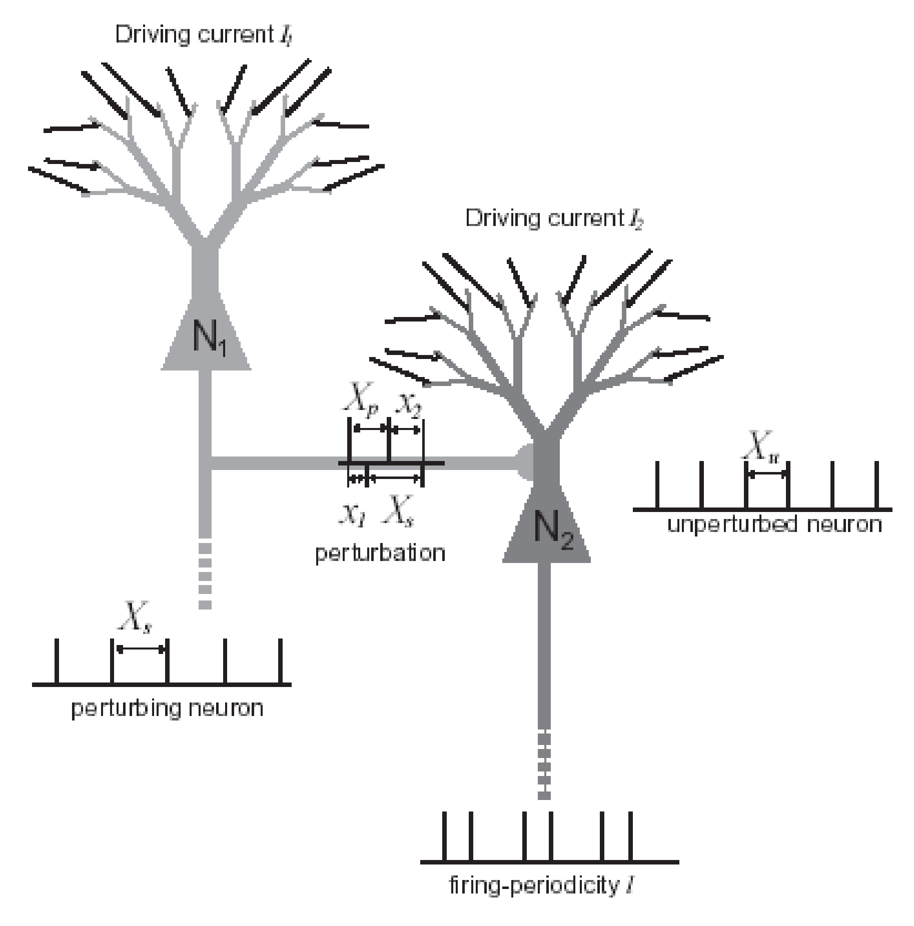
Stoop hypothesis: the generic scheme

Main points of our model of neural computation (Stoop et. al, various publications):

- In a quasi-stationary state, most neurons show limit-cycle behavior.

- Coupling of limit cycles leads to the phenomenon of locking (a generic phenomenon: Huygens!)

- In this way, currents are encoded in periodicities of firing (A/D converter, Huffman-optimal)



$$\phi_2 = \phi_1 + \Omega - g_K(\phi) \mod 1 \qquad \text{where} \quad \Omega = \frac{X_s}{X_u} \quad \text{and} \quad g_K(\phi) = \frac{X_p(\phi)}{X_u}(K)$$

Neuronal noise in the *in vivo* condition

In the in vivo condition, various noise sources affect the „ideal“ limit cycle firing of a neuron:

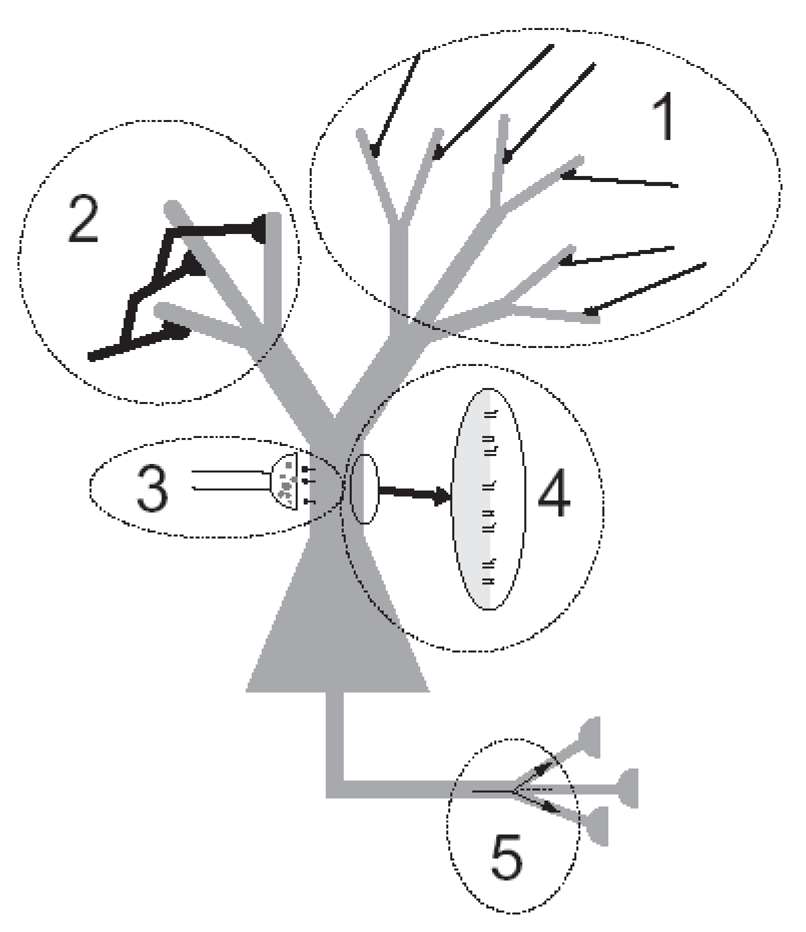
1) Changing background activity.

2) Input delay variability.

3) Several variants of synaptic noise (spontaneous release, varying number / size of vesicles etc.)

4) Several variants of membrane noise (channel noise, thermal effects, lesions etc.)

5) Several variants of conductance variability (axonal branching etc.)



Stoop-Hypothesis: experimental support

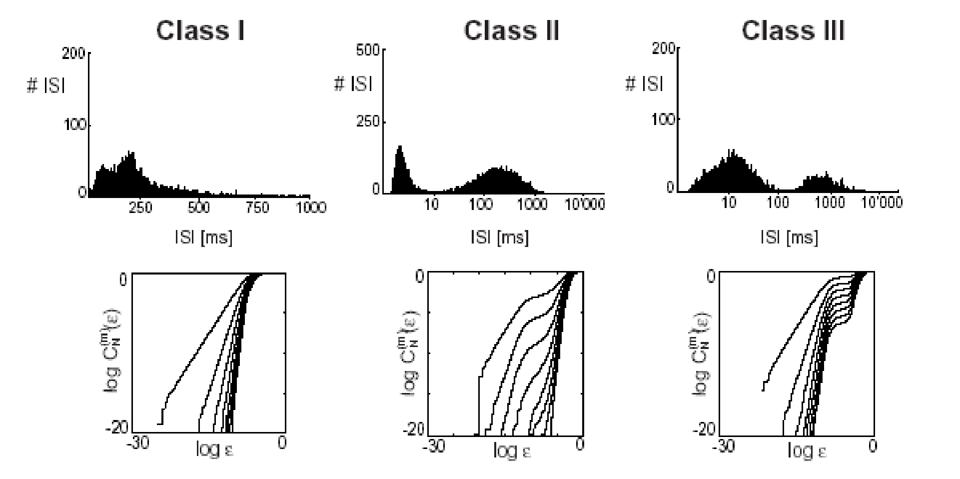
In several publications (Stoop et al), it has been shown that:

- There are three different classes of neuronal firing.

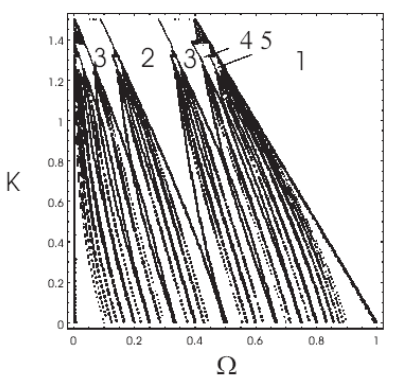
- The Arnold tongue structure is found *in vitro.*

- In model studies, periodicity is preserved for nonconstant driving.

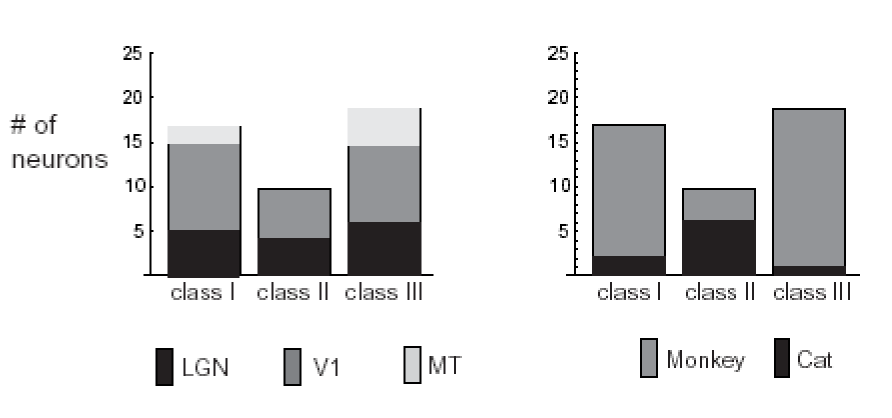
There is also experimental support for two classes of synapses (weak/strong).



(Christen et al, 2004)



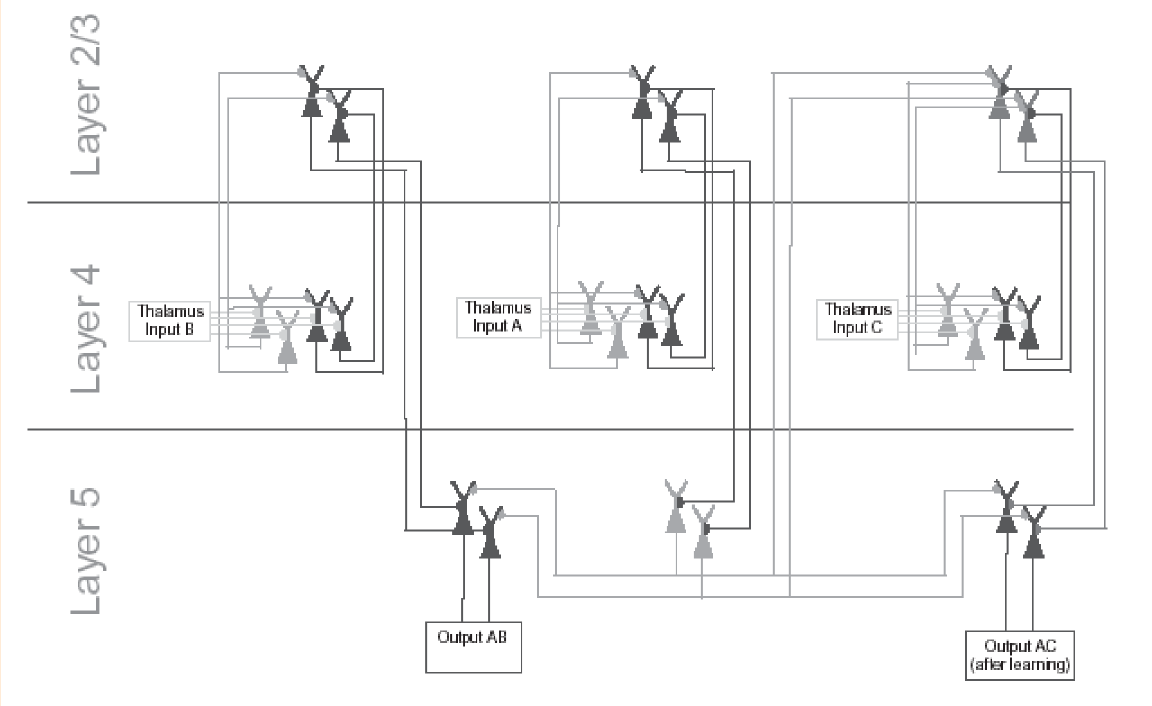
(Stoop et al, 2000)



Stoop-hypothesis: the network

The model integrates several aspects that are recently discussed in neural coding theories:

- The concepts of rate coding and temporal coding are unified.
- „Noise“ has a functional role
- Coincidence firing may serve as a strong perturbation signal.
- LTP/LTD changes input current.



Stoop hypothesis: predictions

Two predictions are of interest for us:

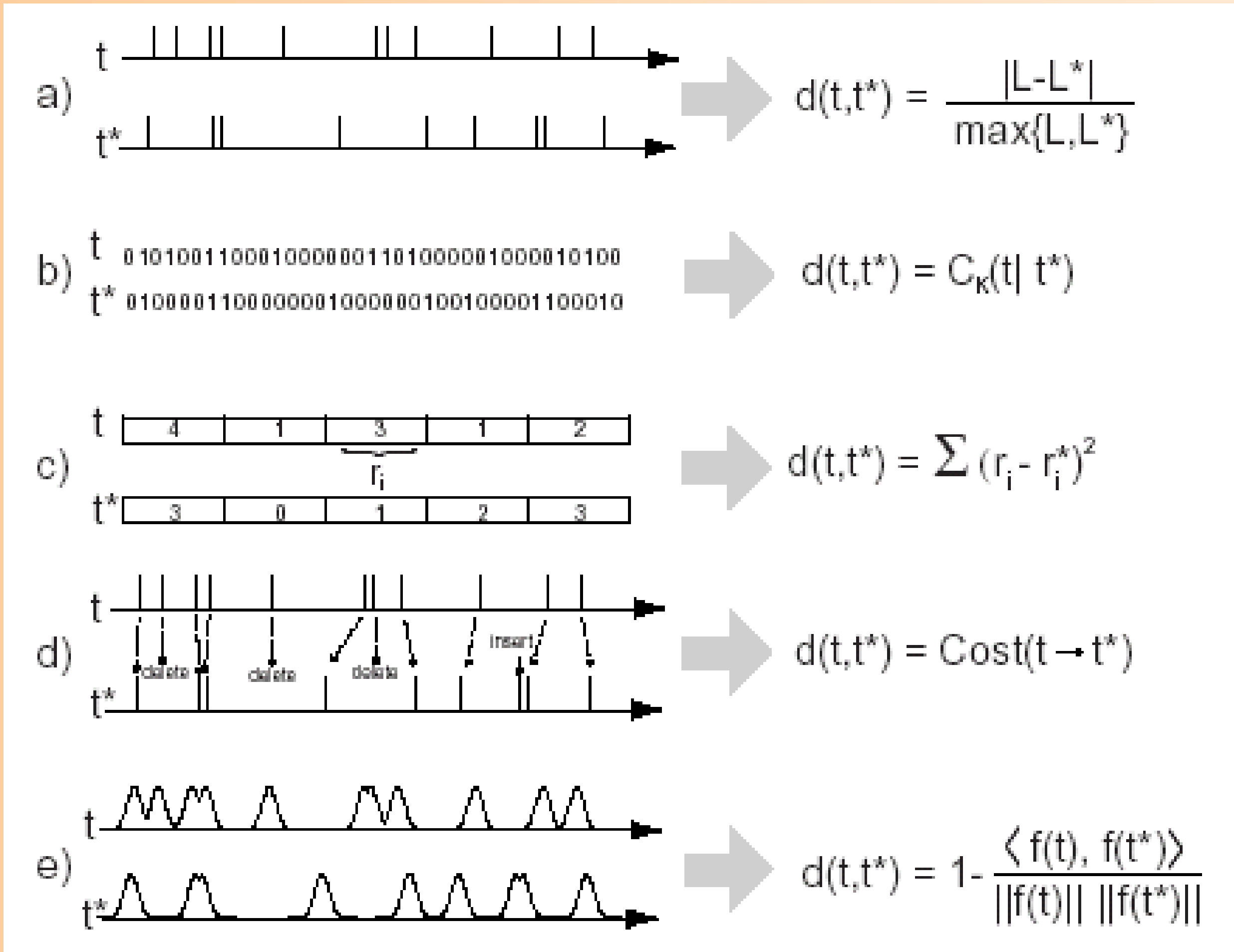
1) We expect different groups of neurons in terms of their firing patterns. We expect a „stabilization-effect" when stimuli are presented. This is a clustering problem:
   - We need a nonparametric clustering algorighm
   - We need an appropriate distance measure

2) We expect different types of reliability on different stages of neuronal information flow: Reliability of information transmission vs. reliability of information processing:
   - We need a distance measure for timing *and* for patterns.

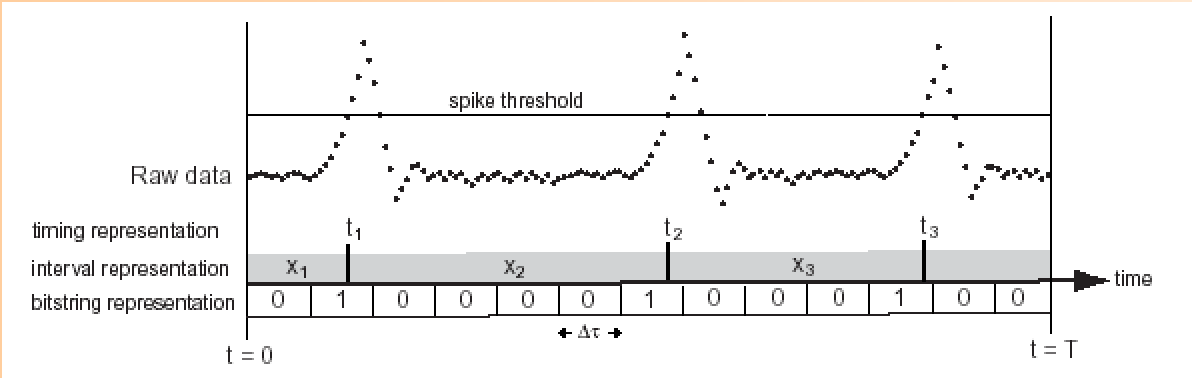
$\Rightarrow$ **Our solution: The Lempel-Ziv-distance**

The first prediction will be investigated in the olfactory system, the second prediction in the visual information processing pathway.

Spike train distance measures



The Lempel-Ziv-distance (1)



Definition 1 *For a bitstring X_n, the* Lempel-Ziv-complexity *$K(X_n)$ of X_n is*

$$K(X_n) = \frac{c(X_n)\log c(X_n)}{n}$$

where $c(X_n)$ is the number of phrases that results from the LZ-coding of X_n.

LZ-coding: The bitstring is sequentially parsed such that the new phrase is not contained in the set of phrases generated so far (the coding proposed in Ziv/Lempel 1978).

The Lempel-Ziv-distance (2)

Definition 2 *For two bitstrings X_n and Y_n of equal length, the Lempel-Ziv-distance $d(X_n, Y_n)$ is:*

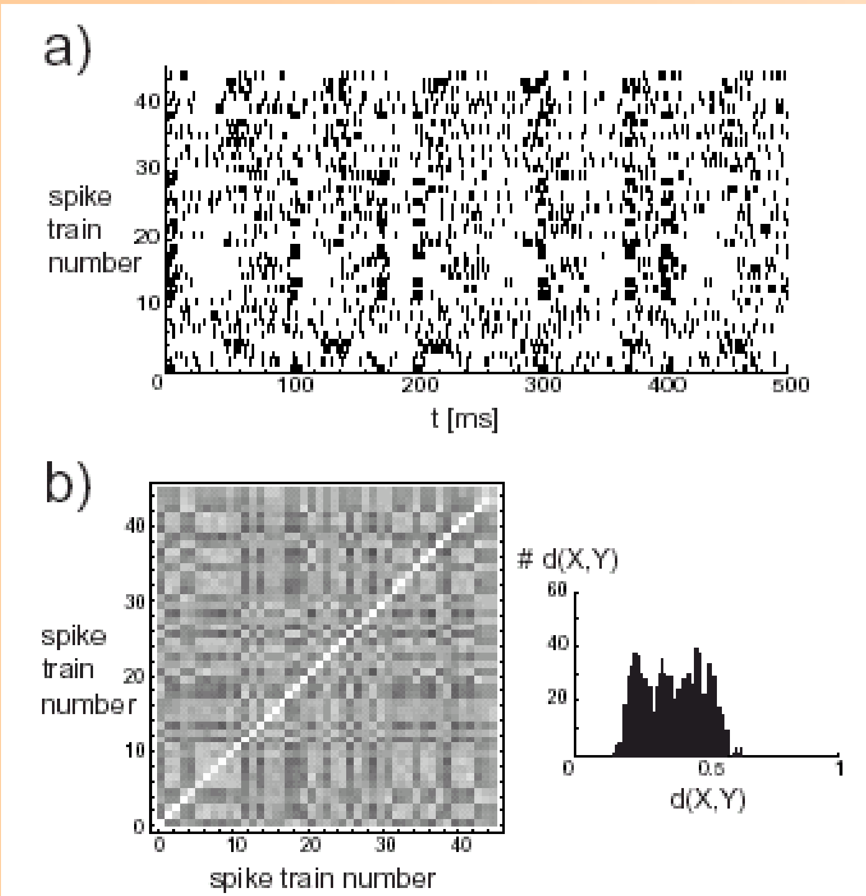
$$d(X_n, Y_n) = 1 - \min\left\{\frac{K(X_n) - K(X_n|Y_n)}{K(X_n)}, \frac{K(Y_n) - K(Y_n|X_n)}{K(Y_n)}\right\}$$

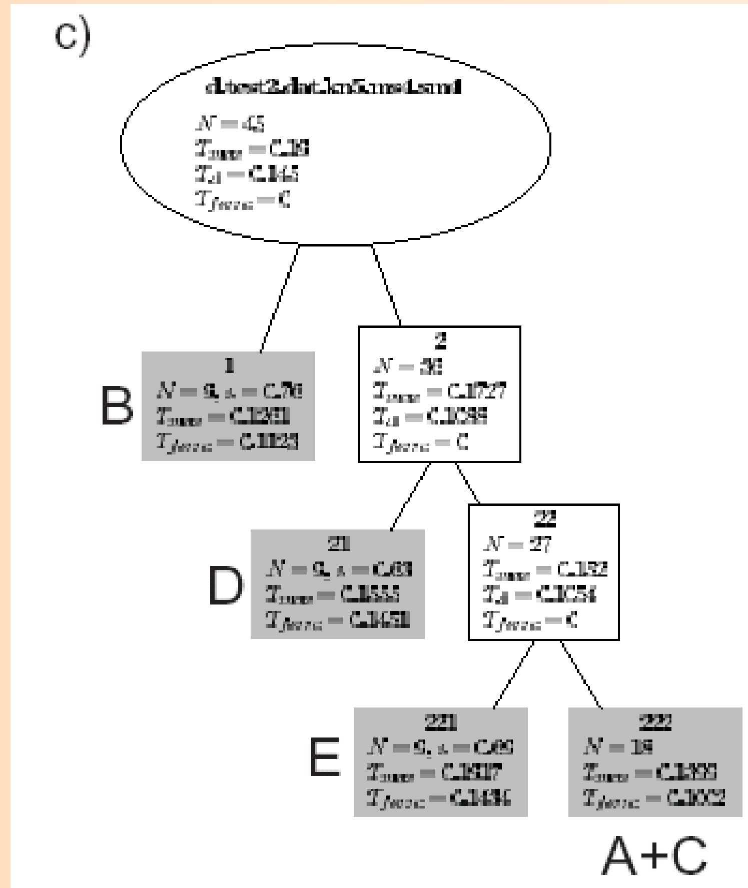
$K(X|Y)$ is obtained by calculating the difference set $P_X \setminus P_Y$ (P_X: the set of phrases that results from a LZ-coding of X).

The denominator $K(X)$ serves as a normalization factor such that $0 \leq d(X,Y) \leq 1$.

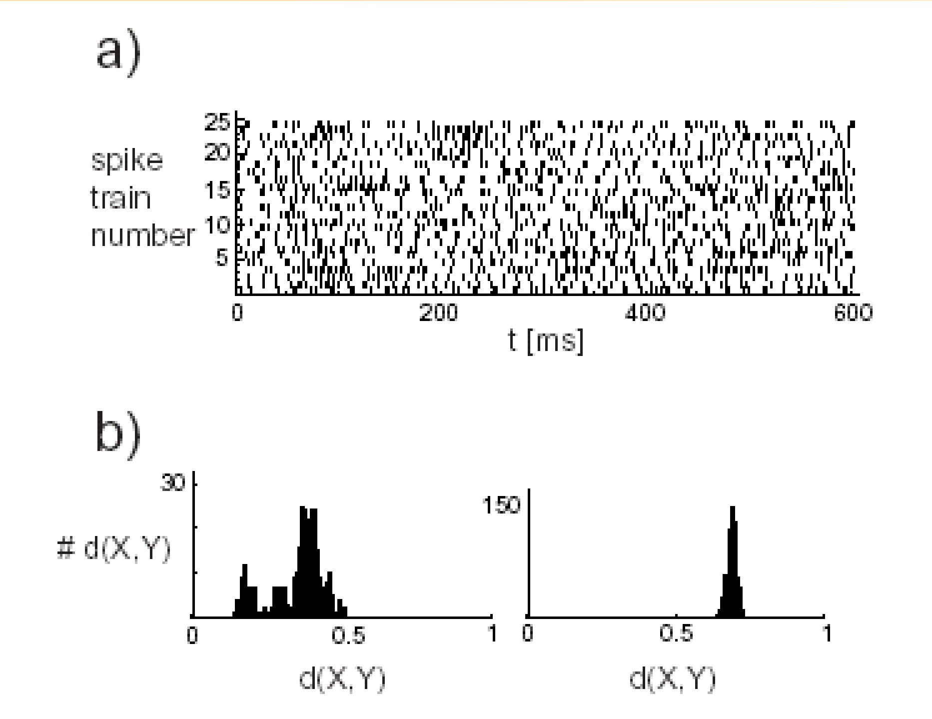
For Kolmogorov-complexity we have $C_K(X) – C_K(X|Y) \approx C_K(Y) – C_K(Y|X)$. But if we approximale C_K with the LZ-complexity for finite strings, we take the minimal value to ensure $d(X_m,Y_n) > 0$ for $m \neq n$.

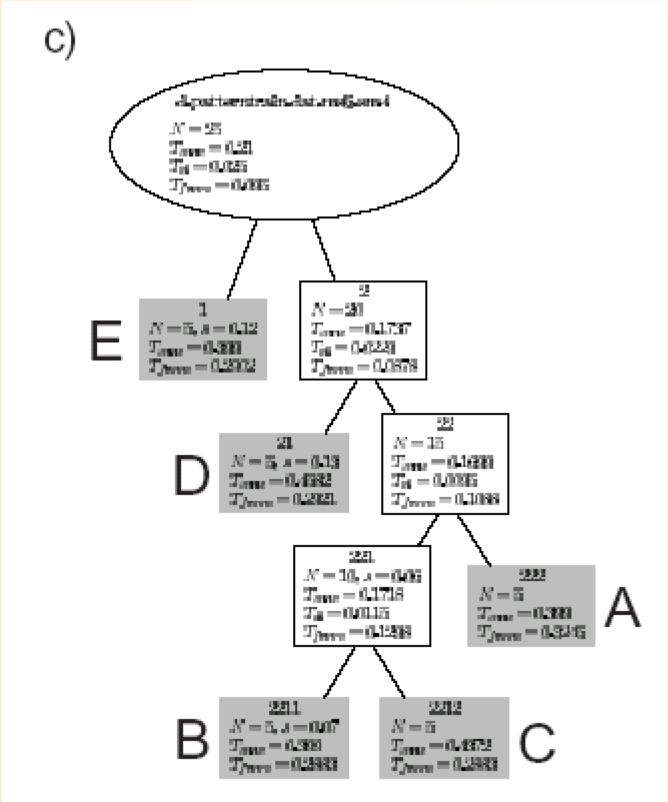
Clustering with the LZ-distance (1)





Clustering with the LZ-distance (2)





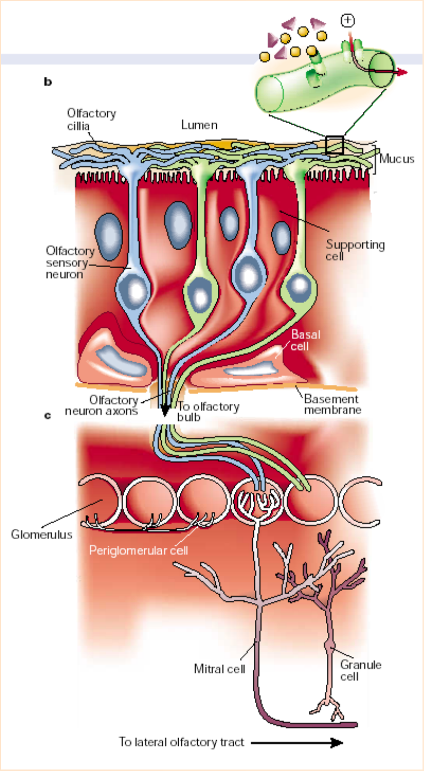
Aplication 1: The olfactory system

Odor is a chemical sense, differing from senses which process physical input (photon density / air pressure / particle velocity).

A major distinction is the synthetic property of olfaction: the ability to assign a specific identity to a great number of component mixtures.

It is assumed that odor identity is encoded in the activity of many cells in the output neurons of the olfactory system (mitral cells).

Olfactory coding is a typical example of a population code.



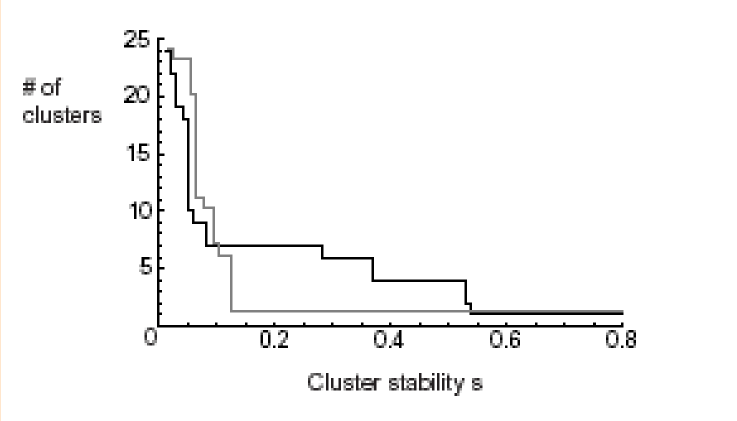
Stabilization, not synchronization

Understanding olfactory coding requires the analysis of functional clustering within a neuronal network of an olfactory sensor.

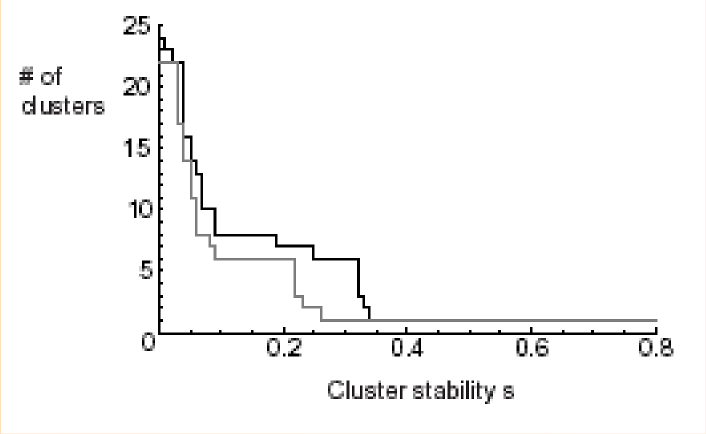
If we apply clustering using the LZ-distance in multi array recor-dings in the olfactory bulb of rats (54 neurons, 48 spike trains recorded before and 48 spike trains during odor presenta-tion), we find the following mean behavior of the network:

- The change in cluster stability signals odor presentation
- This effect is much less present when synchronization determines cluster identity.

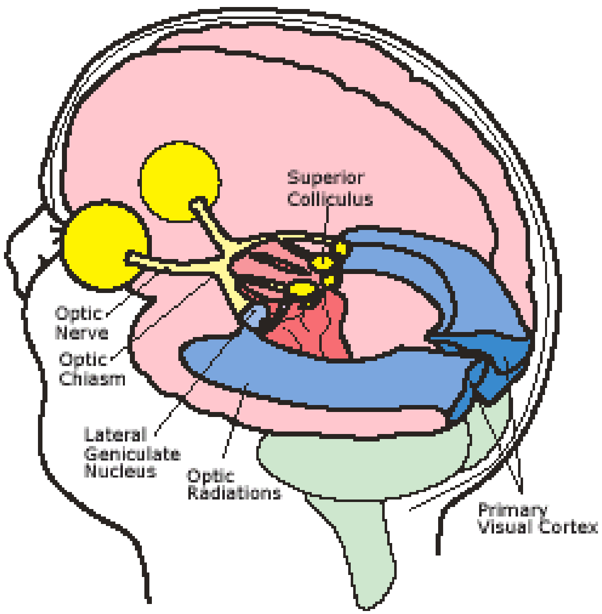
LZ-distance



Distance focussing on coincident firing



Application 2: The visual system



The geniculostriate visual pathway includes the lateral geniculate nucleus, the optic radiations and part of the primary visual cortex

Palmer, Stephen E., (1999). *Vision science: Photons to phenomenology*. Cambridge, MA: The MIT Press

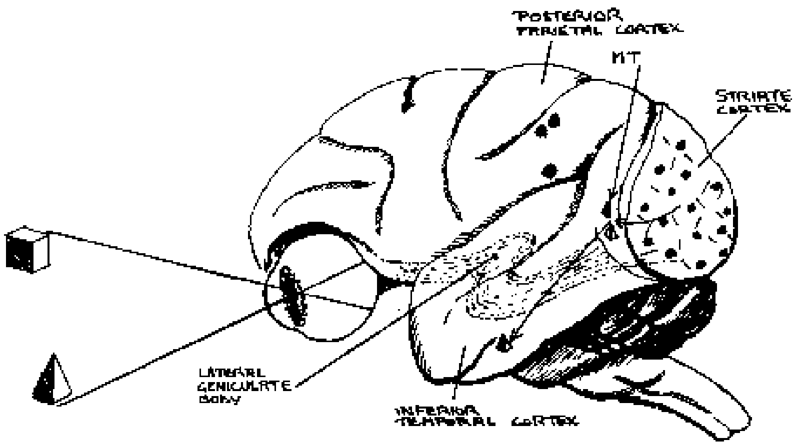
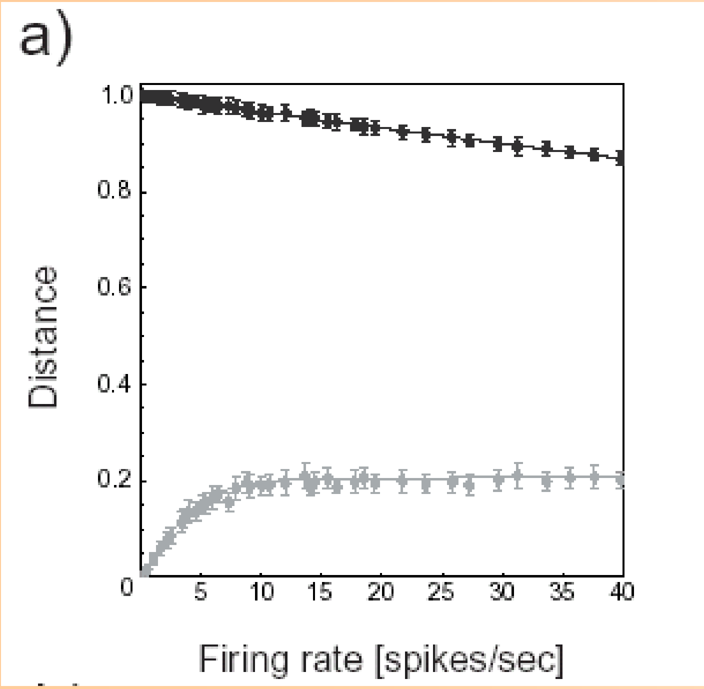
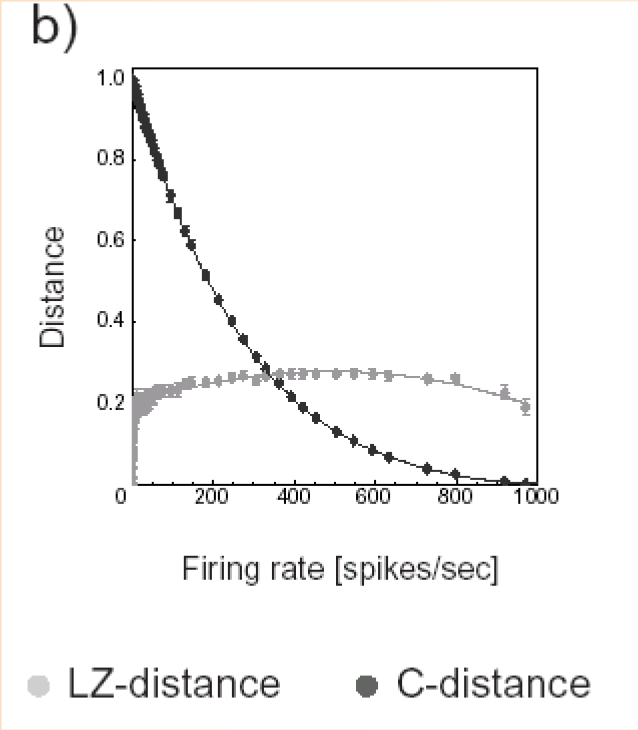


Fig4

Understanding the Brain in the 21st Century, by Max R. Bennett with illustrations by Gillian Bennett

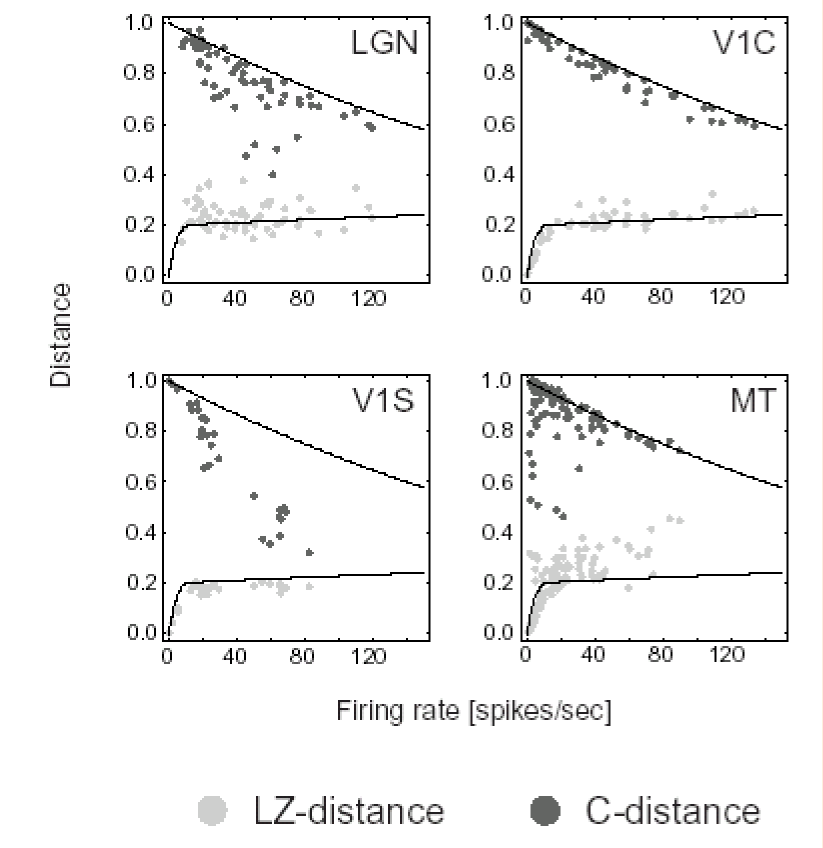
What is firing reliability?

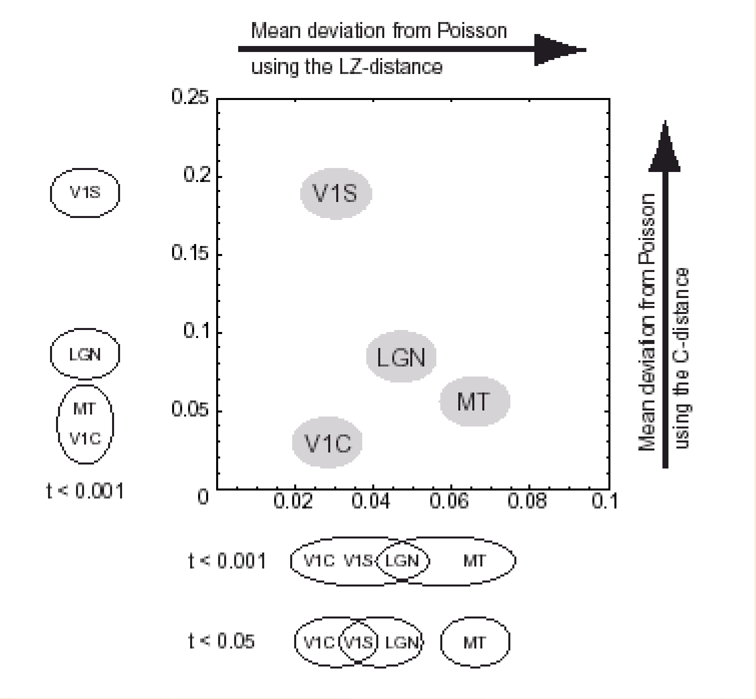




The Poisson process serves as reference for reliability: For a given rate, the mean of the pairwise distance of spike trains is calculated and approximated by a function. The deviation of real data from this function is our measure of reliability.

Firing reliability along the visual pathway





Results: Expectations confirmed

- We find that stable clusters measured in the LZ-paradigm signal odor presentation. In the context of the Stoop hypothesis, these clusters may serve as „processing units“ and the stabilization effect indicates that indeed firing patterns measured in the LZ-paradigm stabilize.
- We find four classes of reliability: High for timing and pattern (LGN), low for timing and pattern (V1 complex), high for timing and low for pattern (V1 simple) and high for pattern and low for timing (MT). This reflects our expectations concerning information transmission reliability and computation reliability.