Information Processing with Pulsed Neural Networks

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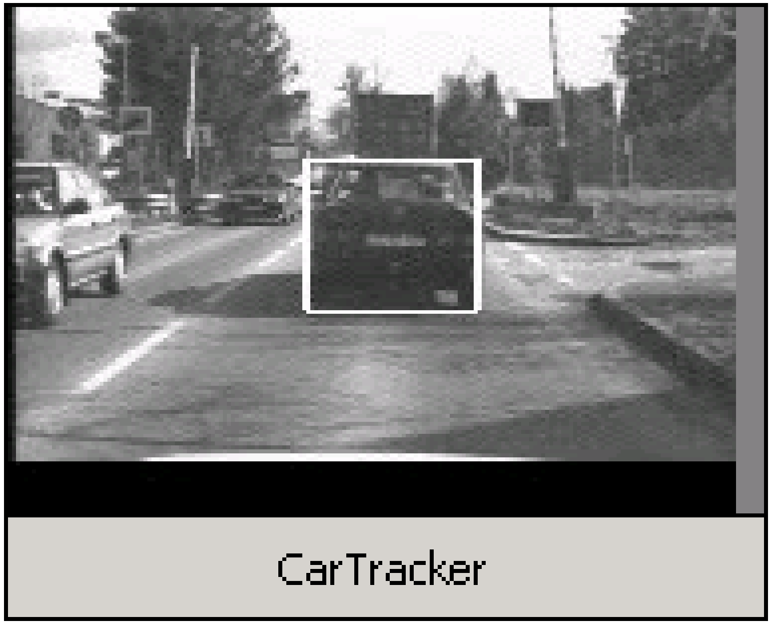
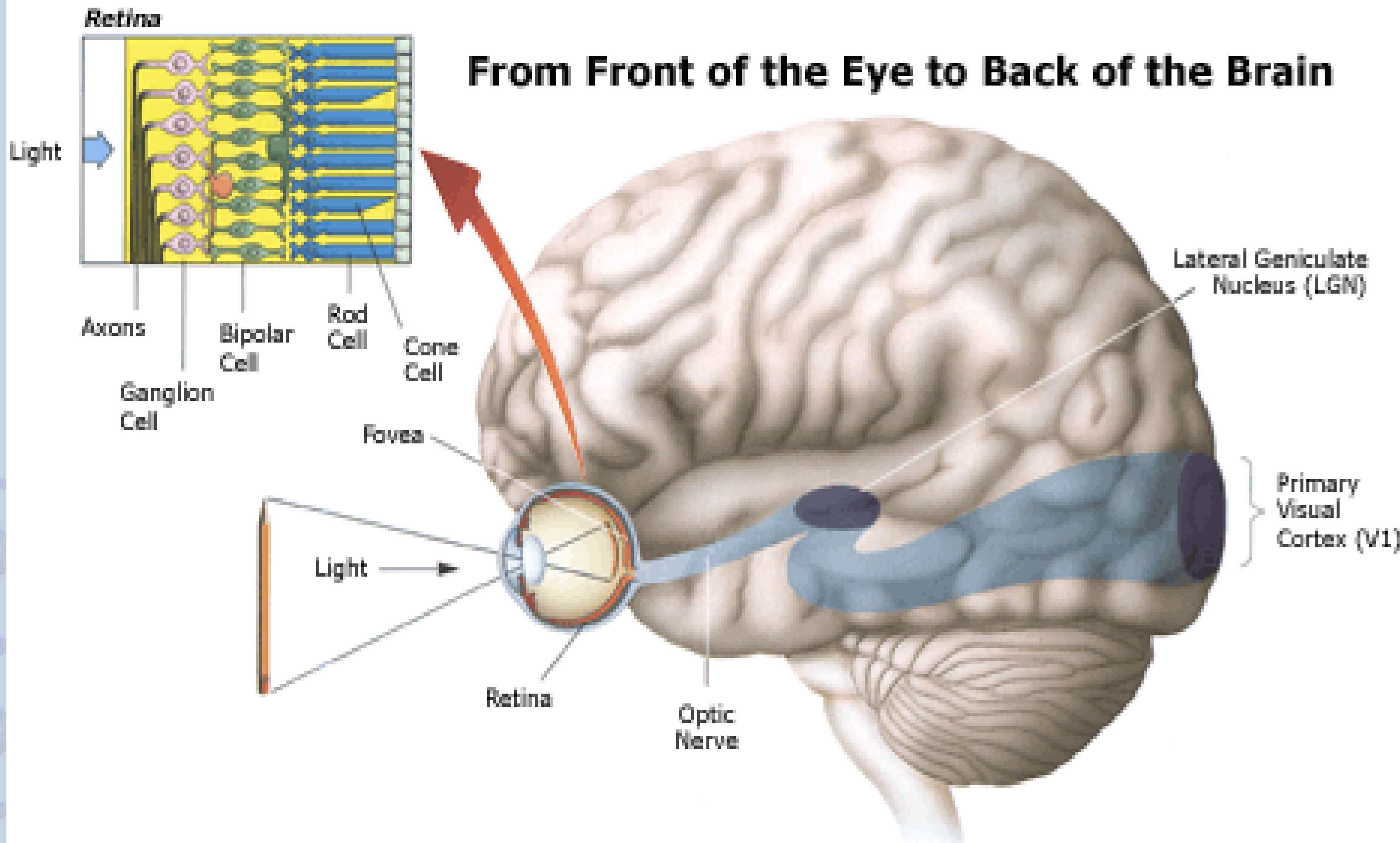
Dilemma (1)



lack of robustness

Dilemma (2)

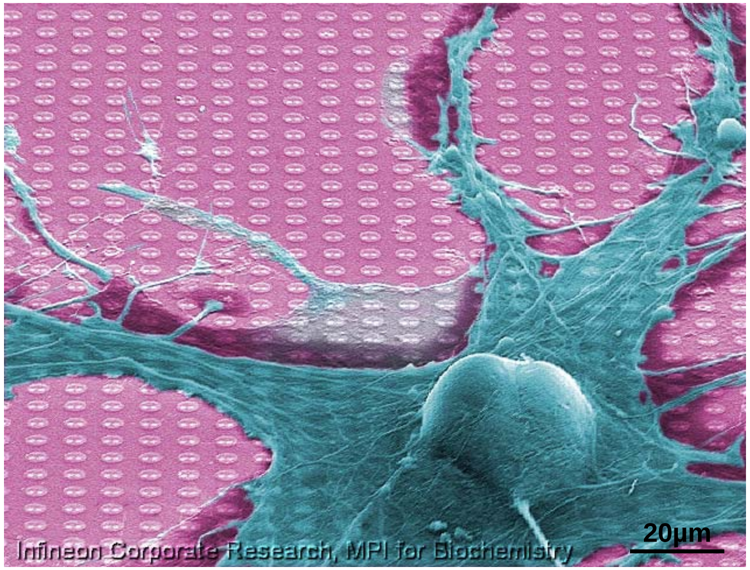


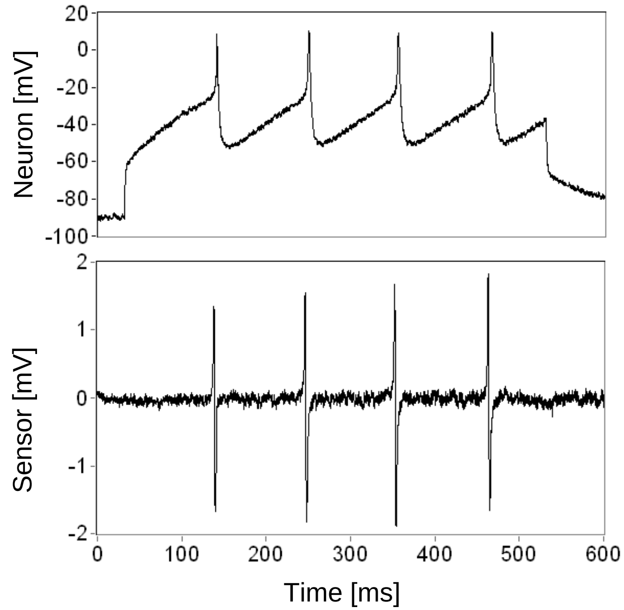
lack of architecture information

Dilemma (3)

Infineon Neurochip

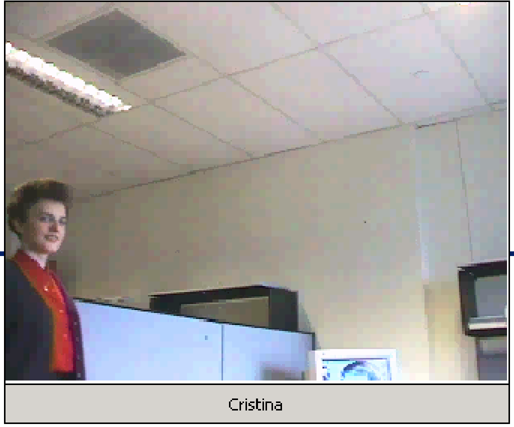
- **Non-invasive long-term recording** of neural tissue.
- **High-density sensor** with 128×128 Sensors in 1×1mm².
- **Extended CMOS-process** with biocompatible high-k surface dielectric.
- **Self-calibration circuitry** and pre-amplification on chip.
- Applications in **neurobiology** and **drug discovery**





Gap between signal processing by few cells and information processing by large arrays

Program



1. Use pulsed IAF neurons and adaptive synapses (inhibitory, excitatory)
2. Use experimental evidence
3. Start from simple, complete vision systems
4. Find basic network structures for information processing
5. Find quantitative ansatz for information processing
6. Demonstrate usefulness for cell phones

Neuron Model

$$k \in R(t_0): \quad a_k(t) = a_k(t_0) + \int_{t_0}^{t} \left[\sum_{l \in S(t_0)} W_{kl}(t') \cdot X_l(t') + W_{k0} \cdot i_k(t') \right] dt'$$

or :

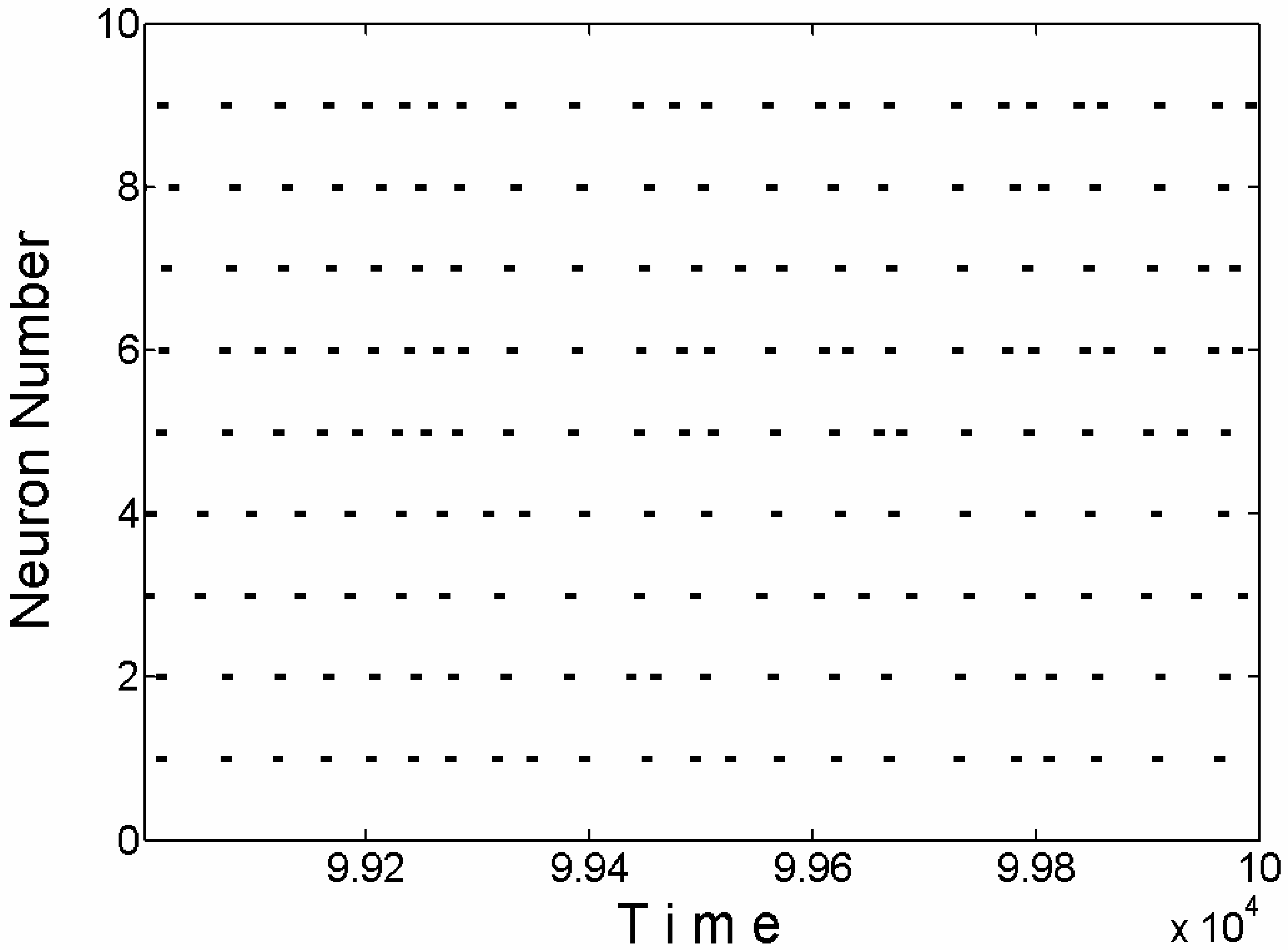
$$da_k / dt = -c \cdot a_k(t) + \sum_{l \in S(t_0)} W_{kl}(t) \cdot X_l(t) + W_{k0} \cdot i_k(t)$$

Rule 1: Reaching the threshold, a neuron resets membrane potential to zero and starts sending a pulse of 1 ms

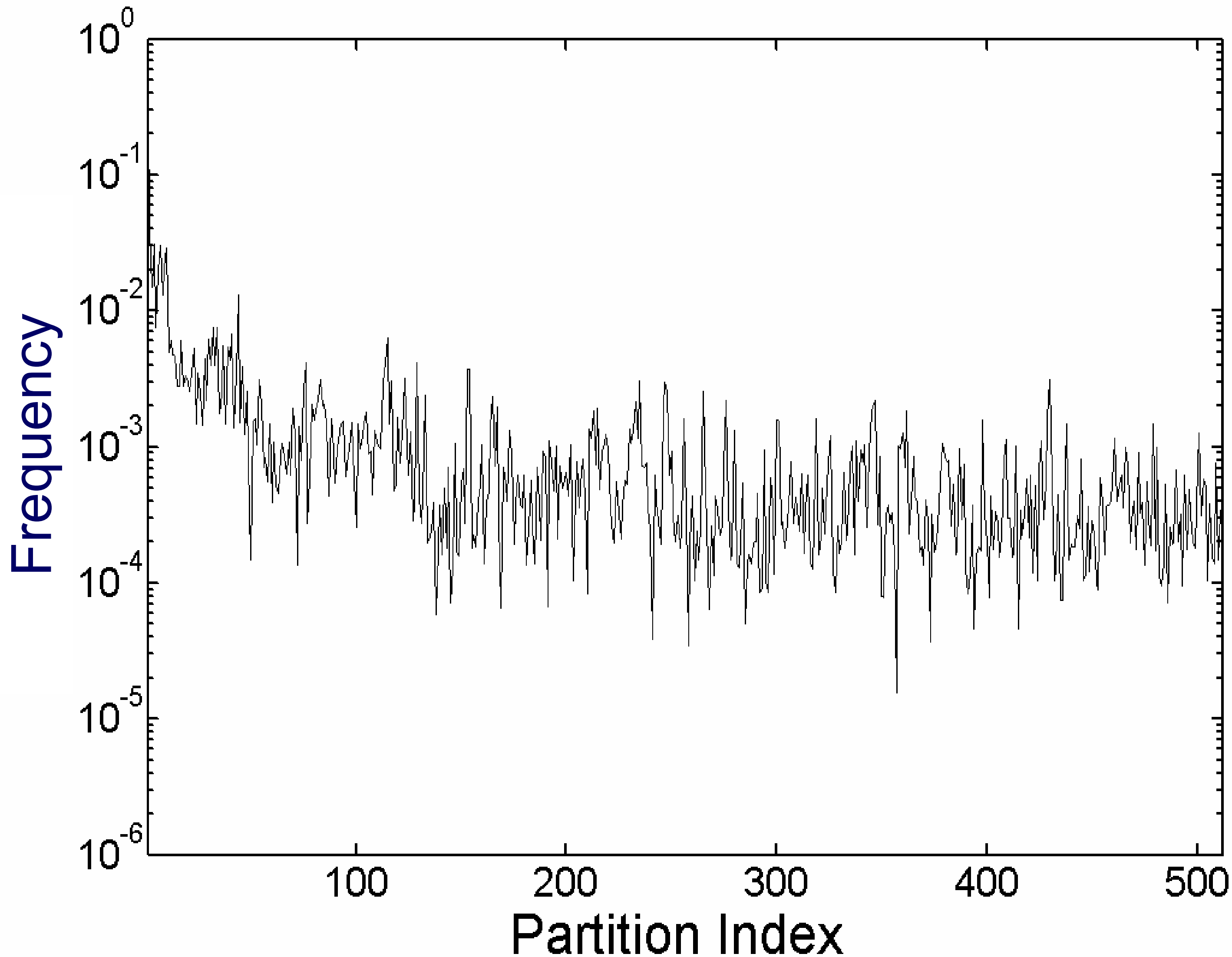
Rule 2: A neuron either receives or sends

➔ deterministic dynamical system

Experiment 1



Experiment 1



Observations

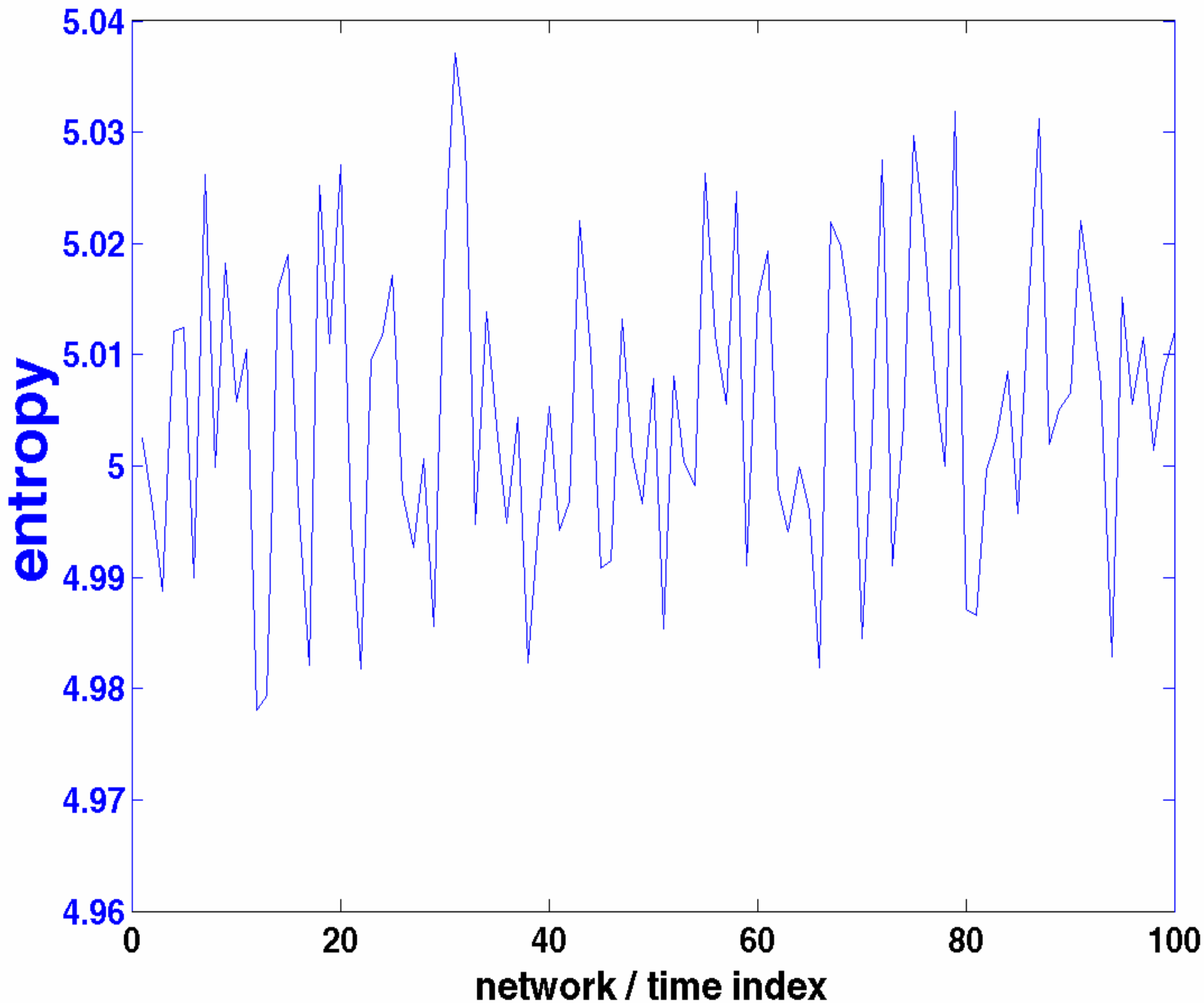
- „Firing patterns don‘t come to an end“
- information processing is not a function of time

➔ Does frequency of firing patterns characterize the net ?

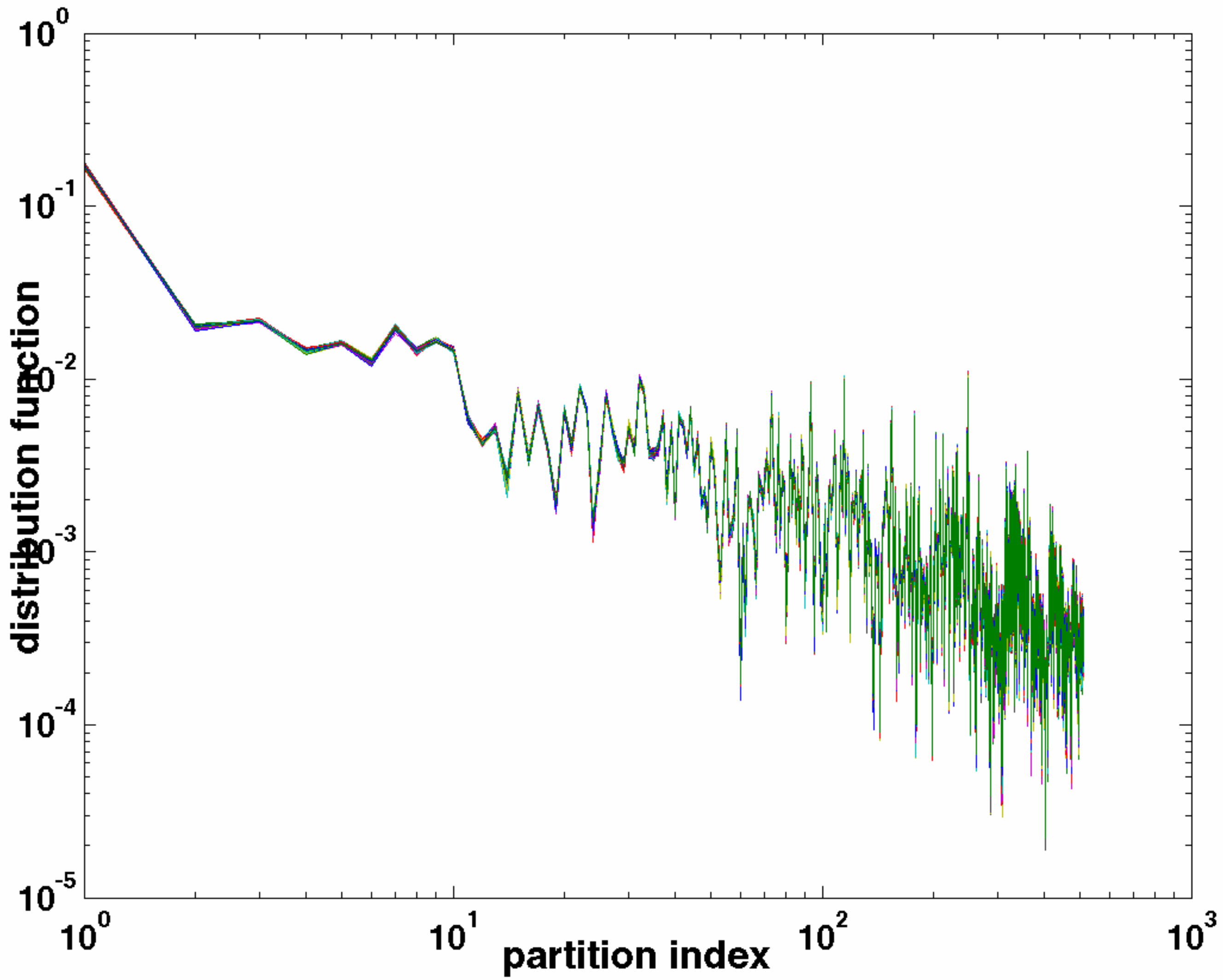
$$I_{net} = -\sum p_n \times \ln p_n$$

Is entropy a reproducible measure of information?

Experiment 2:



Experiment 2



Findings

• distribution function of fp‘s is independent of initial conditions

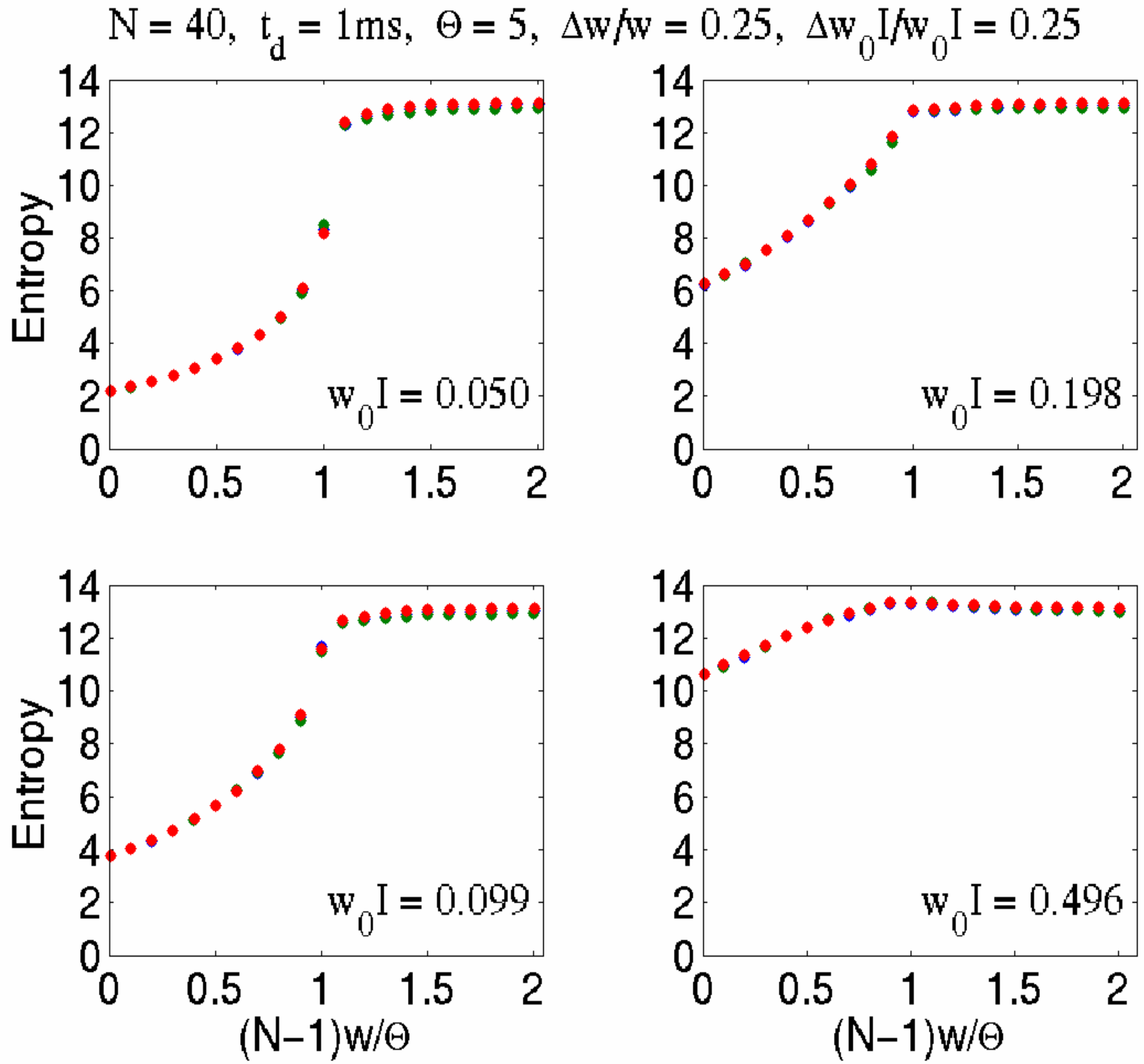
➔ $I_{net} = - \sum p_n \times \ln p_n$

is a reproducibly measurable quantity

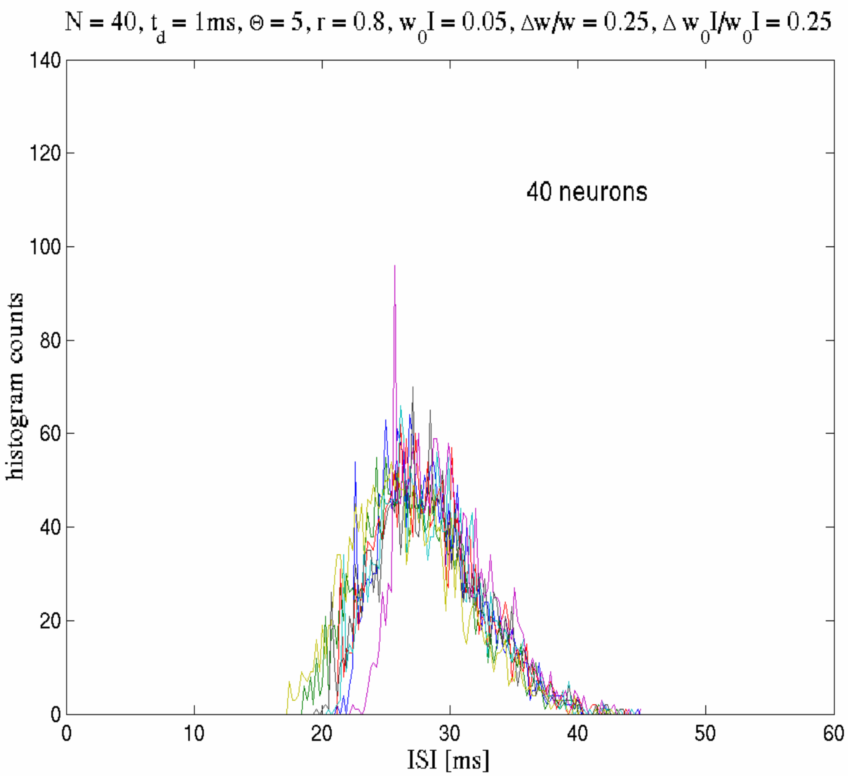
Entropy as a function of mean synaptic weight

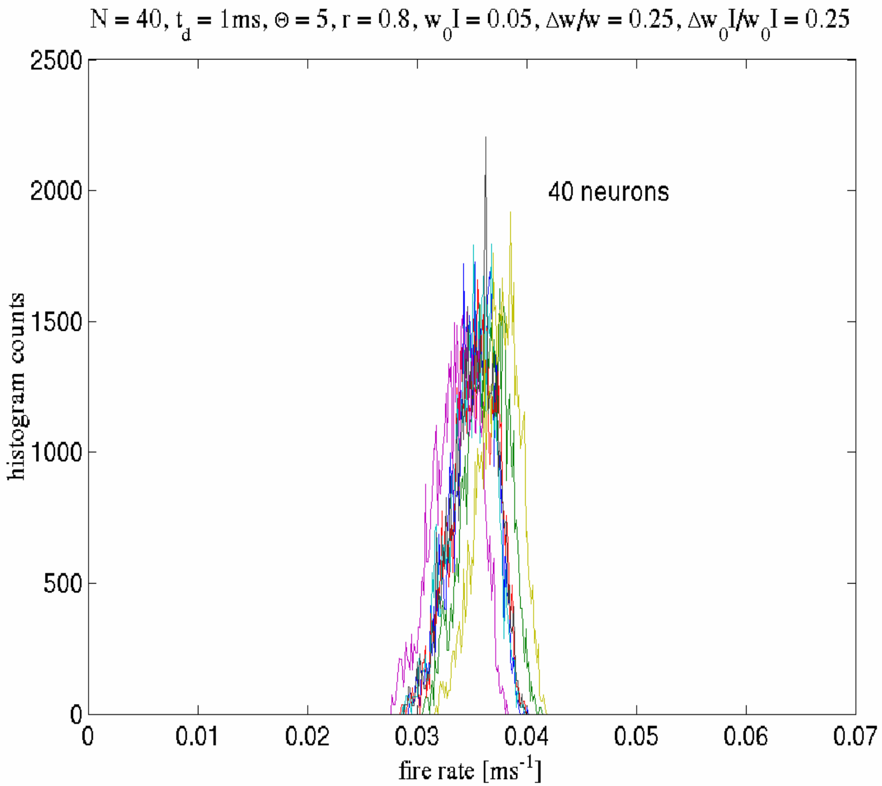
Each color corresponds to a different realization of w_{ij}

Network size: 40 neurons



Network size: 40 neurons





ISI

Fire Rate

Synapse Model
(proposed by U. Ramacher, April 99)

$$k \in E(t_0), l \in S(t_0):$$

$$\dot{W}_{kl} = -\gamma \cdot W_{kl} + \mu \cdot \left(a_k(t) - \frac{\theta}{2} \right) \cdot \chi(X_l)$$

$$else: \qquad \dot{W}_{kl} = -\gamma \cdot W_{kl}$$

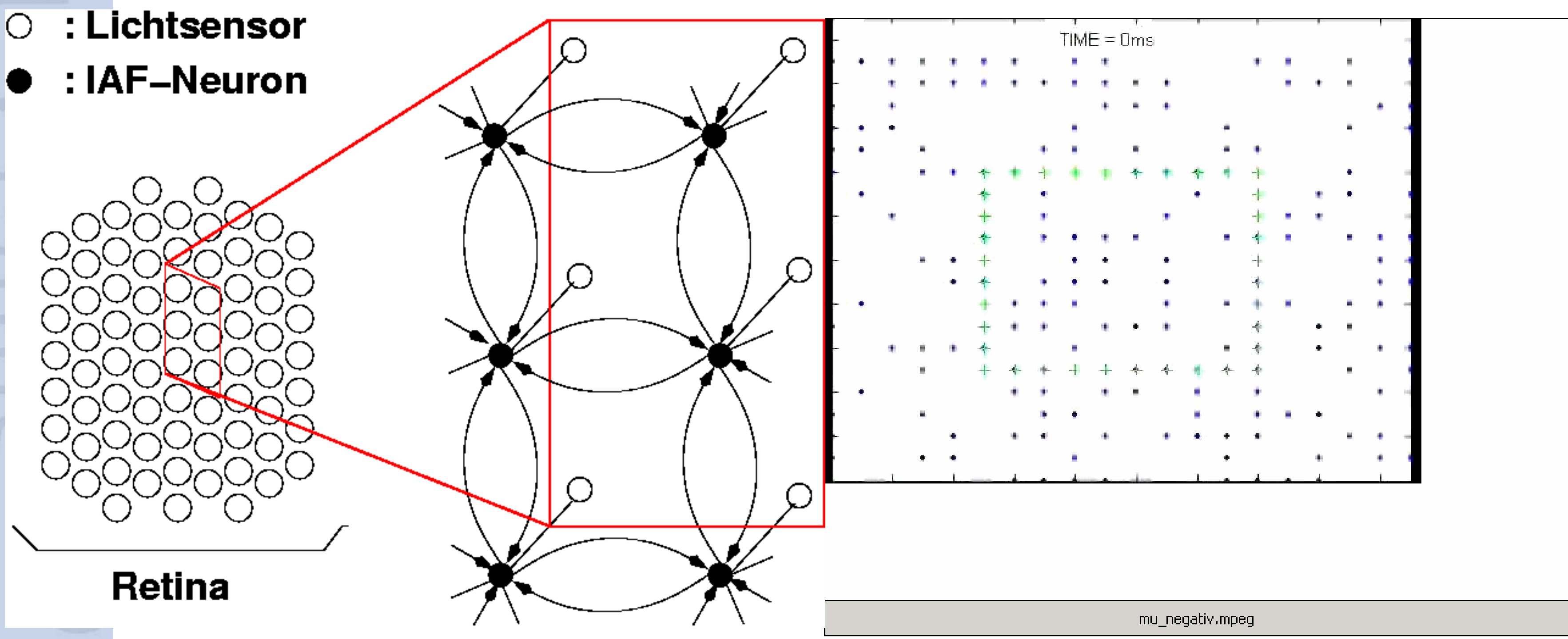
Adaptation rule : local, causal, simple

$$\ddot{W}_{kl} + \gamma \cdot \dot{W}_{kl} - \mu \cdot W_{kl}(t') \cdot X_l =$$

$$\mu \cdot \left(\sum_{l' \in S(t_0)} W_{kl'}(t') \cdot X_{l'} + W_{k0} \cdot i_k(t') + a_k(t_0) - \frac{\theta}{2} \right)$$

μ negative

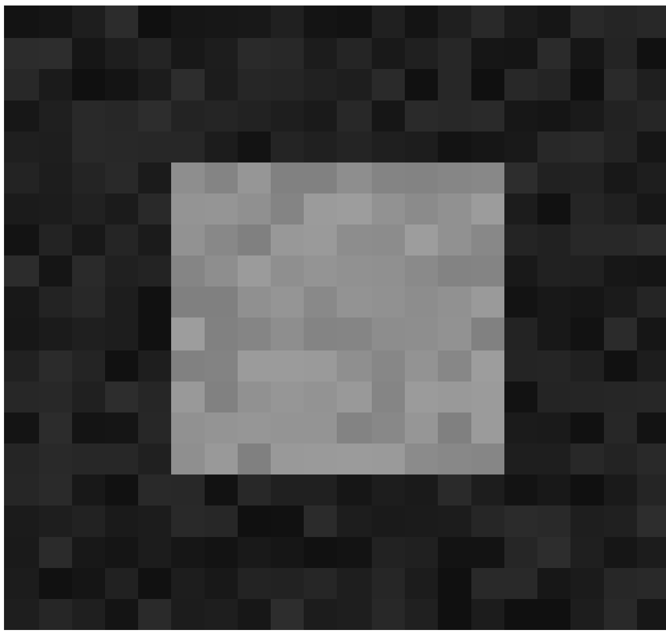
- 20 x 24 pixels , each connected to a neuron by a constant synapse
- adaptive synapses connecting neighboured neurons

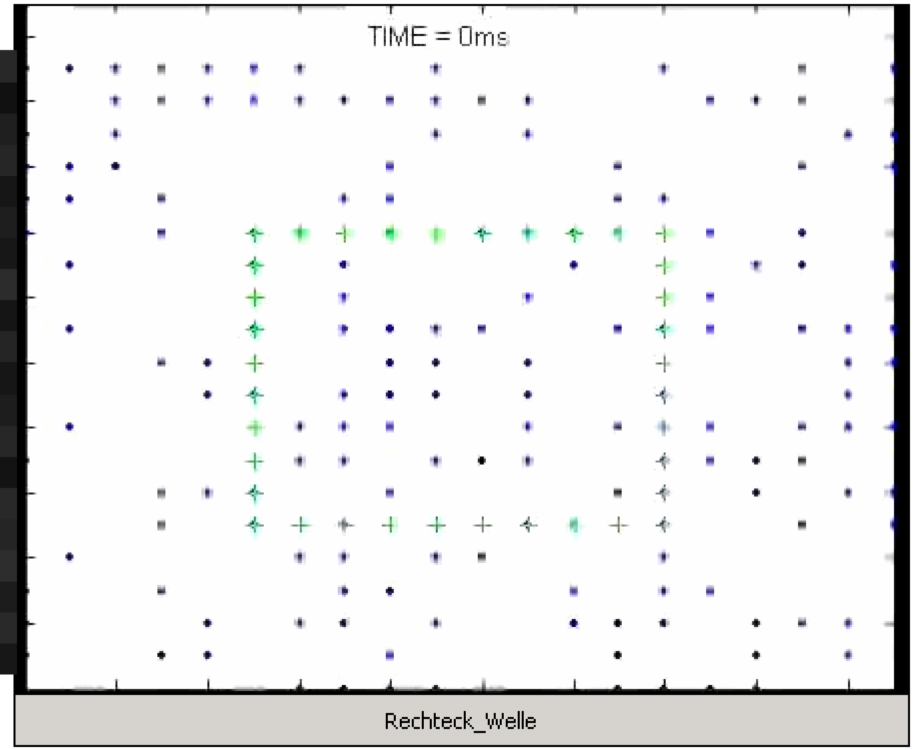


synapses = coupled system of damped oscillators

µ positive

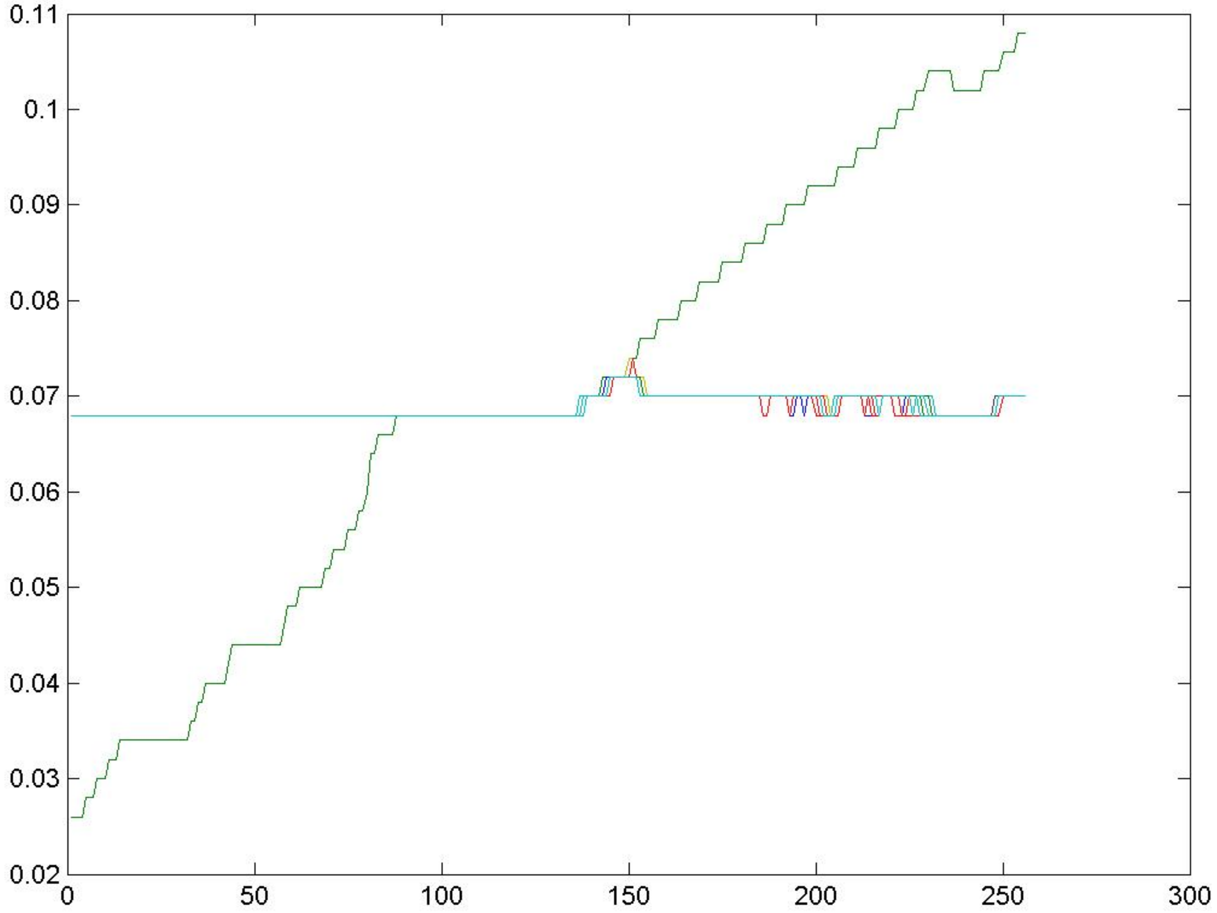
20x24 pixel, 10% noise



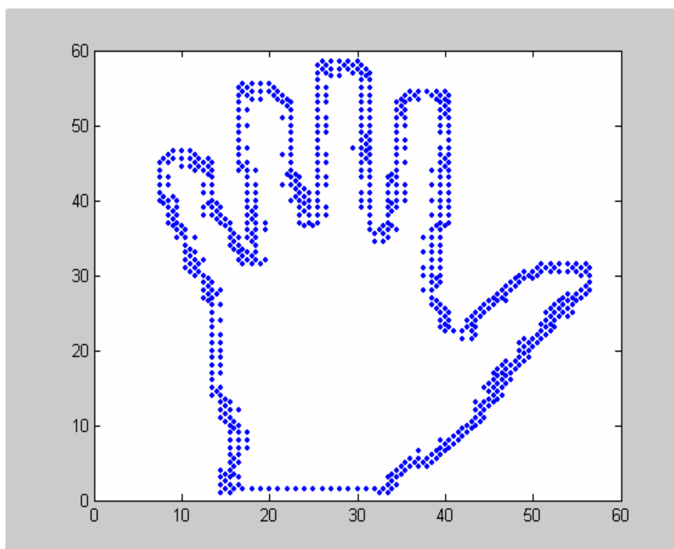


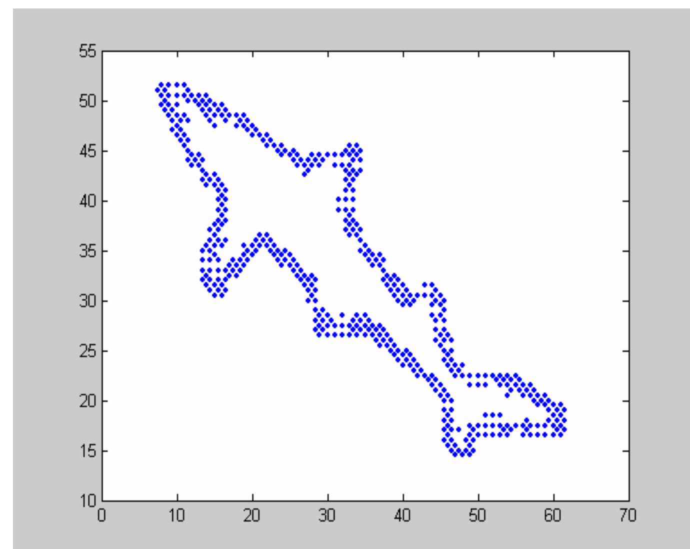
synapses = coupled system of damped exponentially rising and falling „elements“

Spot Detector = Illumination Encoder

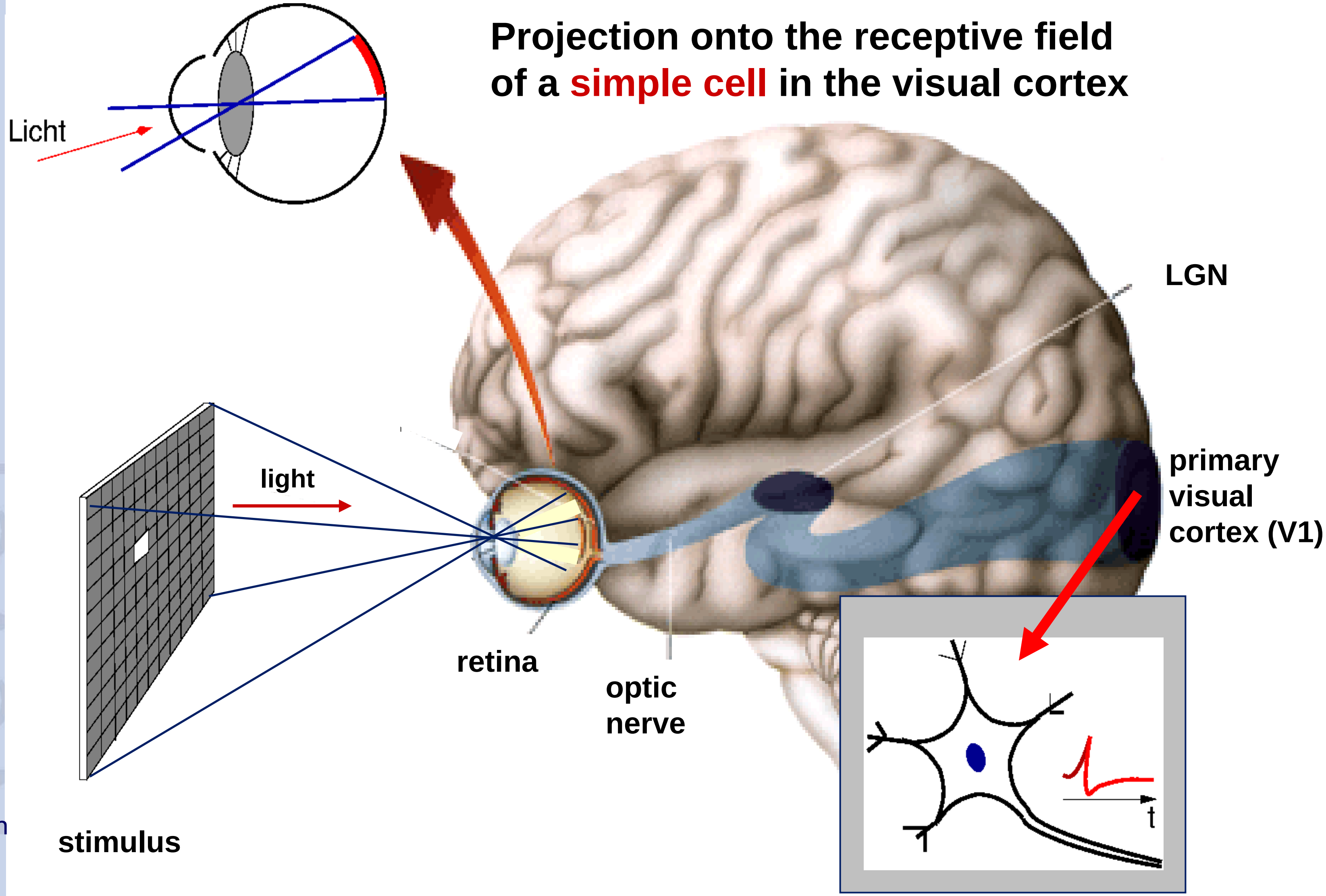


Pixels: 64 x 64

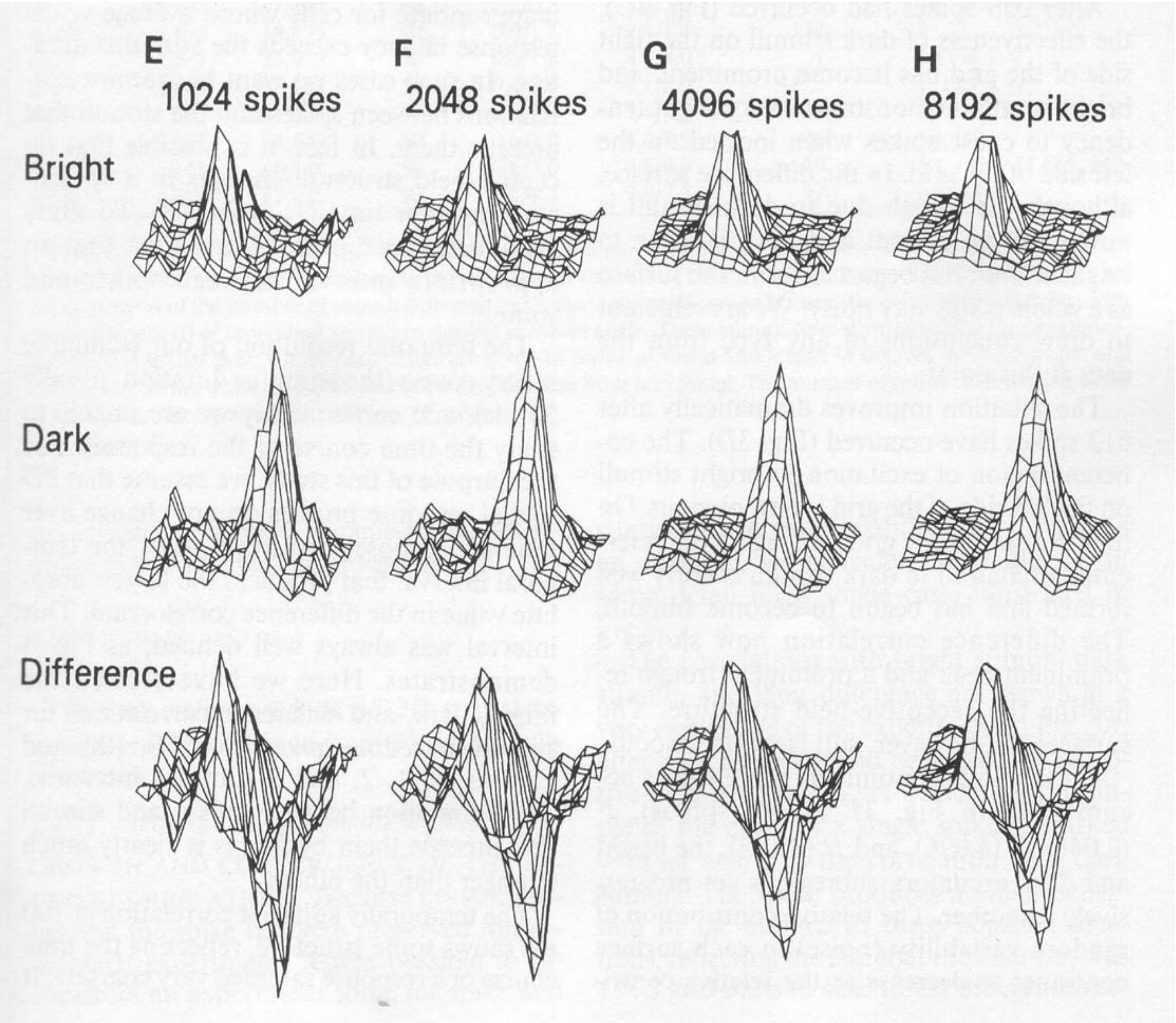




Projection onto the receptive field of a simple cell in the visual cortex

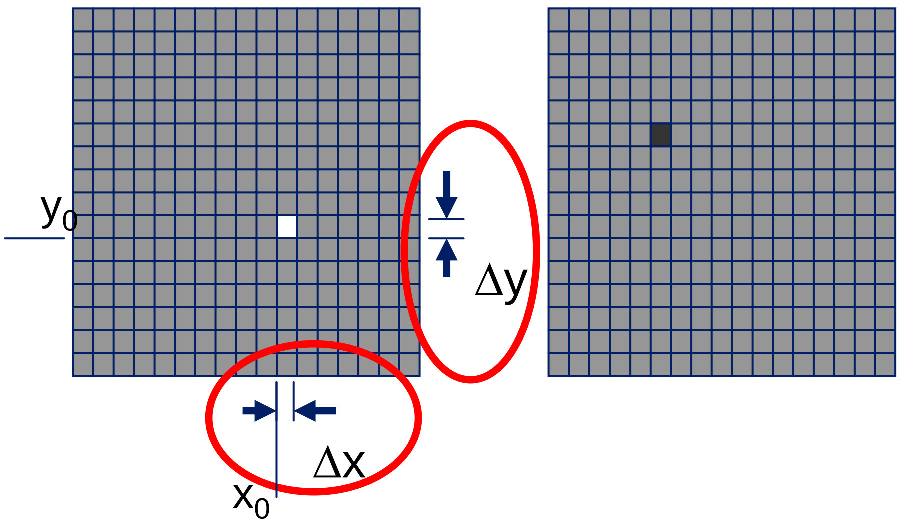


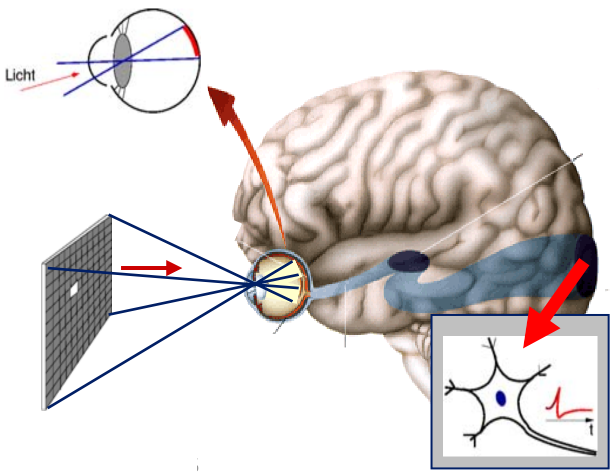
convergence



Modeling the Experiment

Bright Stimulus　　　*Dark* Stimulus



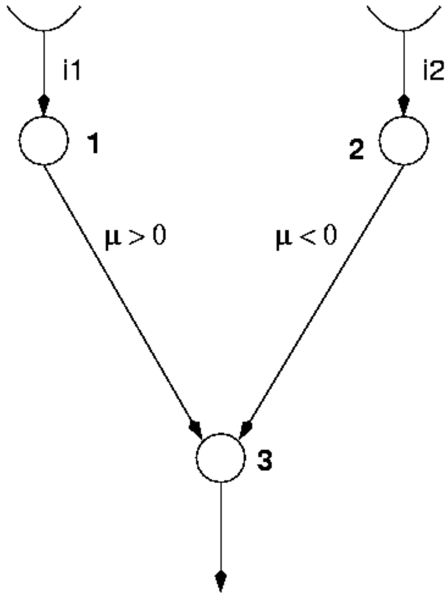


Stimuli projected onto RF of a Simple Cell

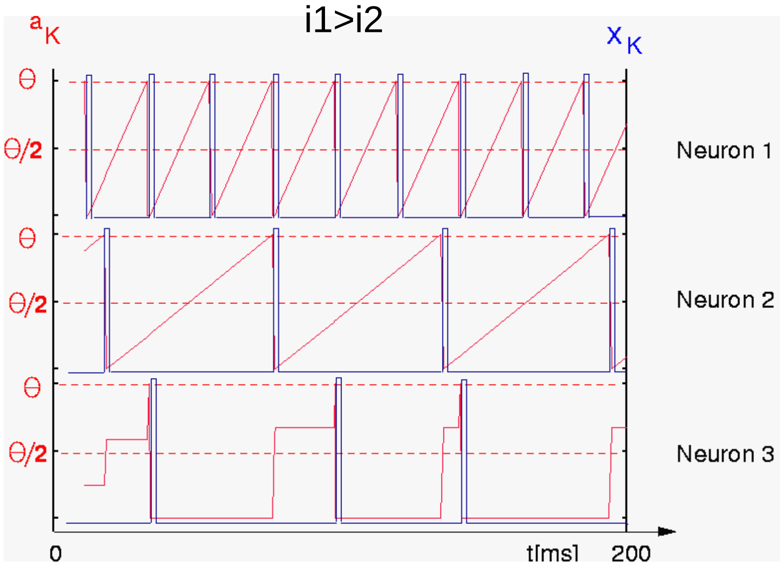
$$\Pi(x_0, y_0) \approx (H - B) \cdot \iint_{(x_0, x_0+\Delta x)\times(y_0, y_0+\Delta y)} G_i(x, y)\,dxdy$$

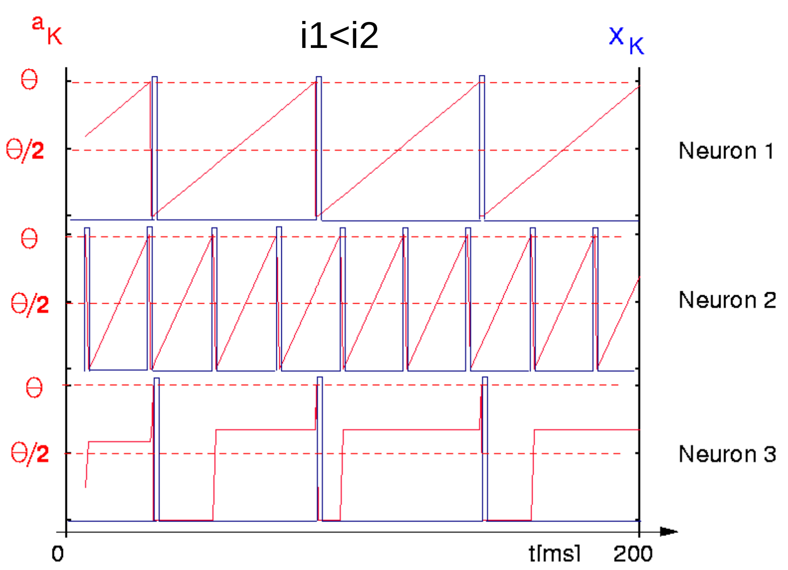
Π: measured pulse rate **G_i**: Gabor function **H**: Spot Intensity **B**: Background Intensity

Pulse difference detector (1)

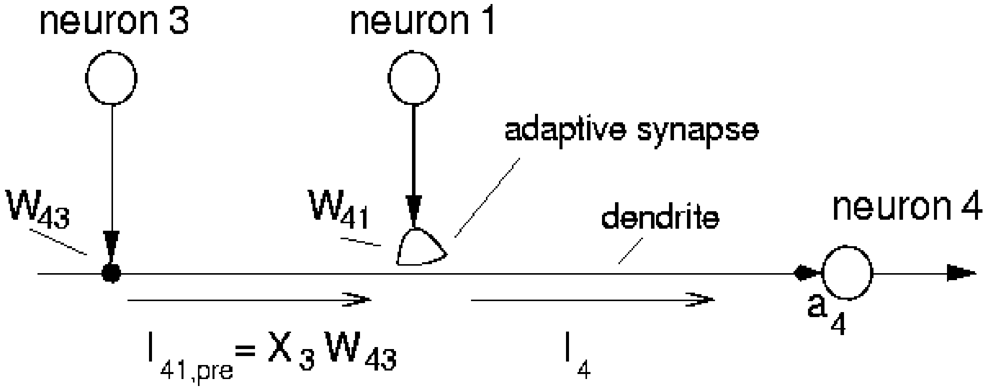


$$\dot{W}_{KL} = -\gamma \cdot W_{KL} + \mu \cdot \left(a_K(t) - \frac{\theta}{2} \right) \cdot \chi(X_L)$$





Pulse difference detector (2)

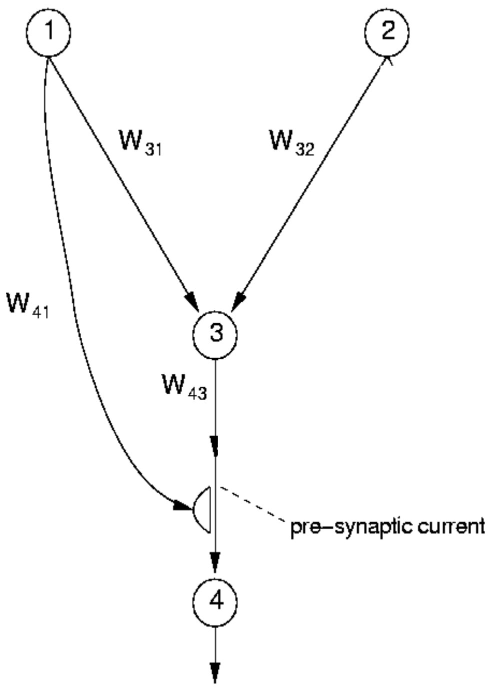


Dynamics of the Synapse W_{41}:

$$\frac{dW_{KL}}{dt} = -\gamma \cdot (W_{KL} - W_{\infty}) + \mu \cdot (I_{pre} - I_{\theta}) \cdot W_{KL} \cdot \chi(X_L)$$

$$\mu < 0 \quad , \quad I_{pre} - I_g > 0 \quad , \quad W_{KL} \geq 0$$

Pulse difference detector (3)



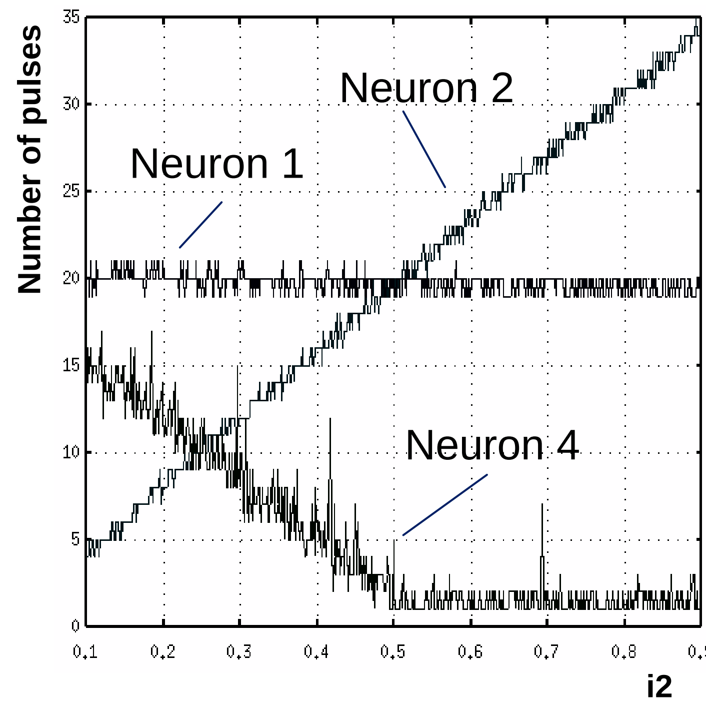
W_{31} adaptive, membrane
$\mu>0$
$\mu=12\ ms^{-2}$
$\gamma=0.1\ ms^{-1}$

W_{32} adaptive, membrane
$\mu<0$
$\mu=-12\ ms^{-2}$
$\gamma=0.1\ ms^{-1}$

W_{41} adaptive, dendrite
$\mu=-500 ms^{-2}$
$\gamma=1.6\ ms^{-1}$
$W_{00}=0.025$

W_{43} , W_{42} constant
$W=0.025$

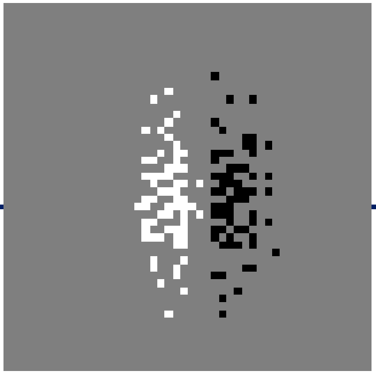
Characteristic

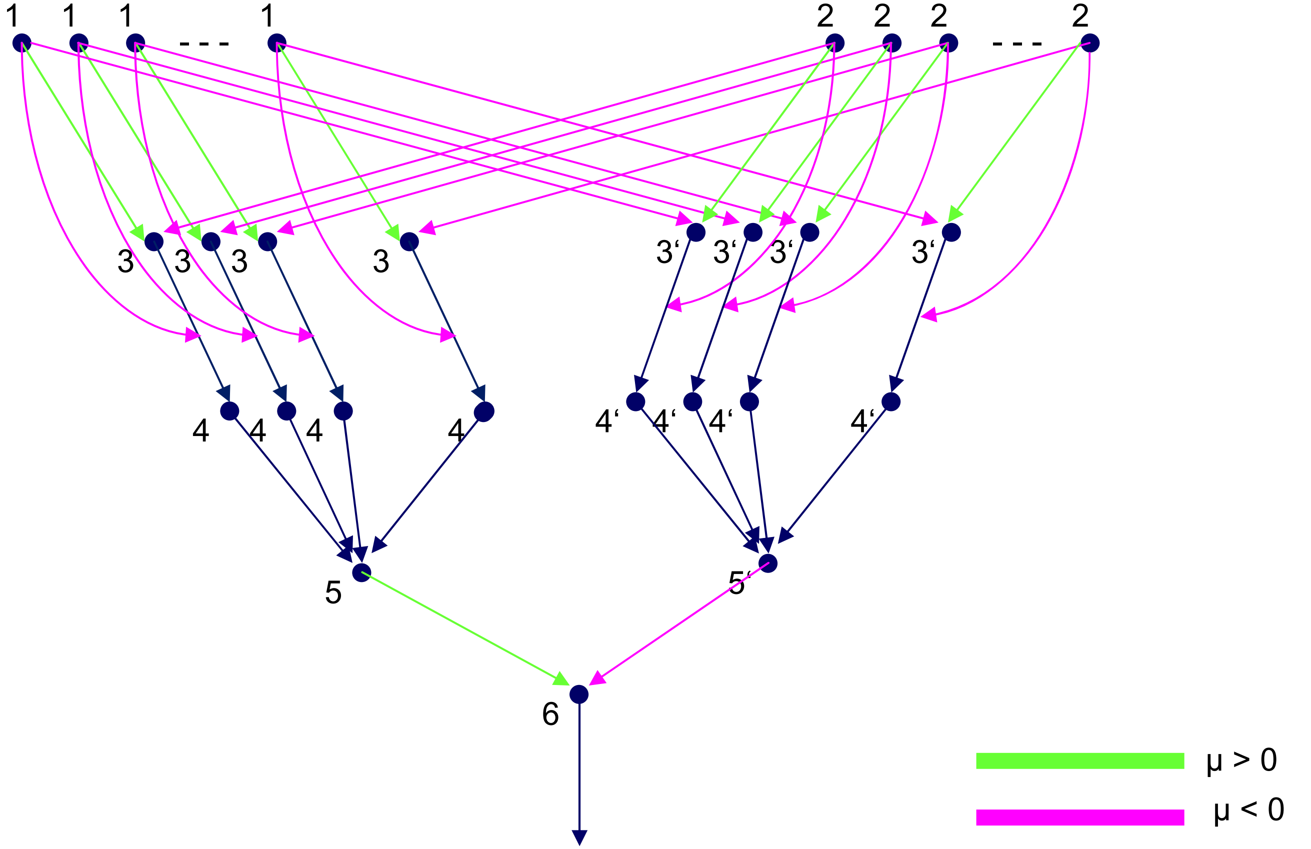


i_1 = **0.5**
Θ = 1
W_{K0} = 0.08
t_d = 1ms
T = 0.5s

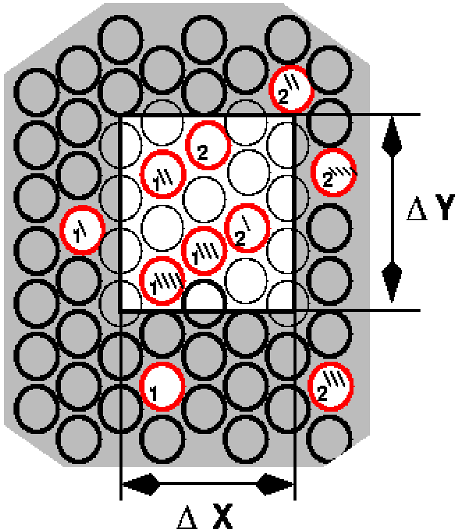
Architecture of feature detector

(proposed by A. Heittmann, 2003)





Shaping the response-profile of the detector



section of the retina

$$N_i^1(x_0, y_0) = \iint_{(x_0,x_0+\Delta x)\times(y_0,y_0+\Delta y)} \rho_i^1(x,y)\,dxdy$$

$$N_i^2(x_0, y_0) = \iint_{(x_0,x_0+\Delta x)\times(y_0,y_0+\Delta y)} \rho_i^2(x,y)\,dxdy$$

$$\Pi(x_0, y_0) = \frac{W_{K0}}{\Theta}\cdot(H-B)\cdot(N_i^1(x_0,y_0) - N_i^2(x_0,y_0))$$

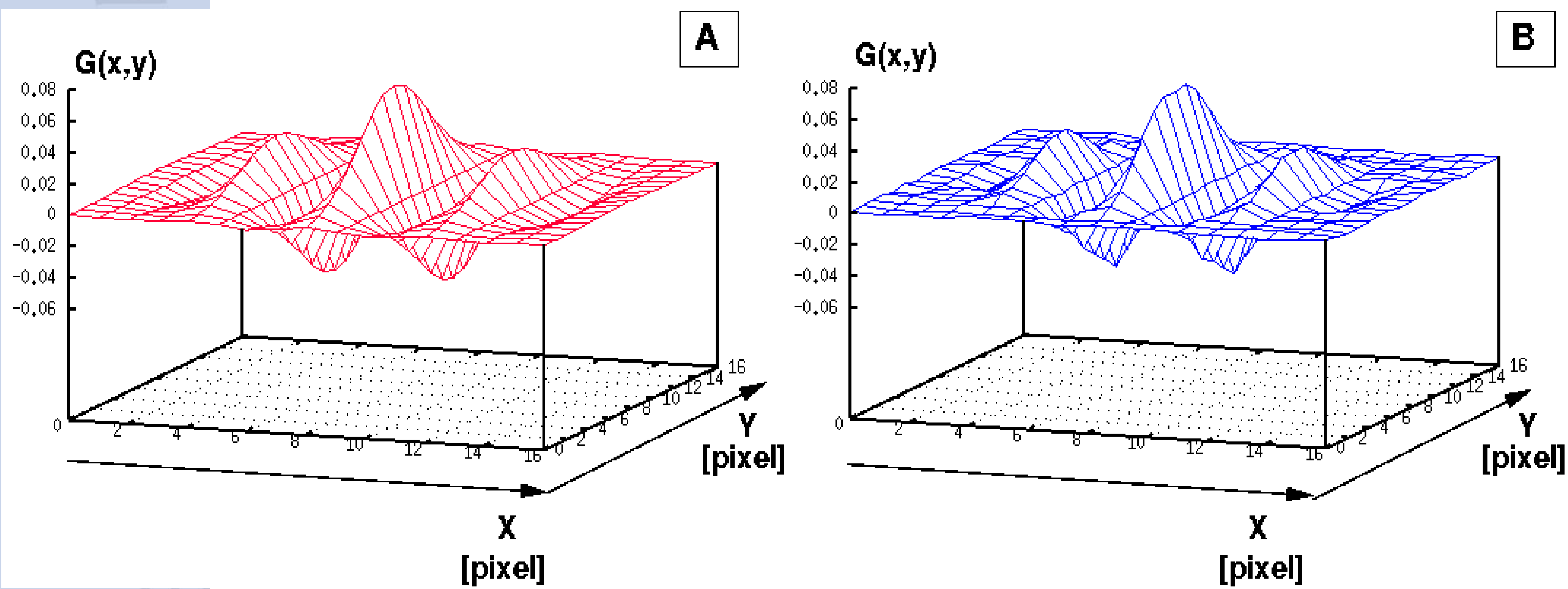
$$\approx (H-B)\cdot\iint G_i(x,y)\,dxdy$$

$$\Rightarrow \rho_i^1(x,y) - \rho_i^2(x,y) = \frac{\Theta}{W_{K0}} G_i(x,y)$$

H: Spot Intensity **B**: Background Intensity

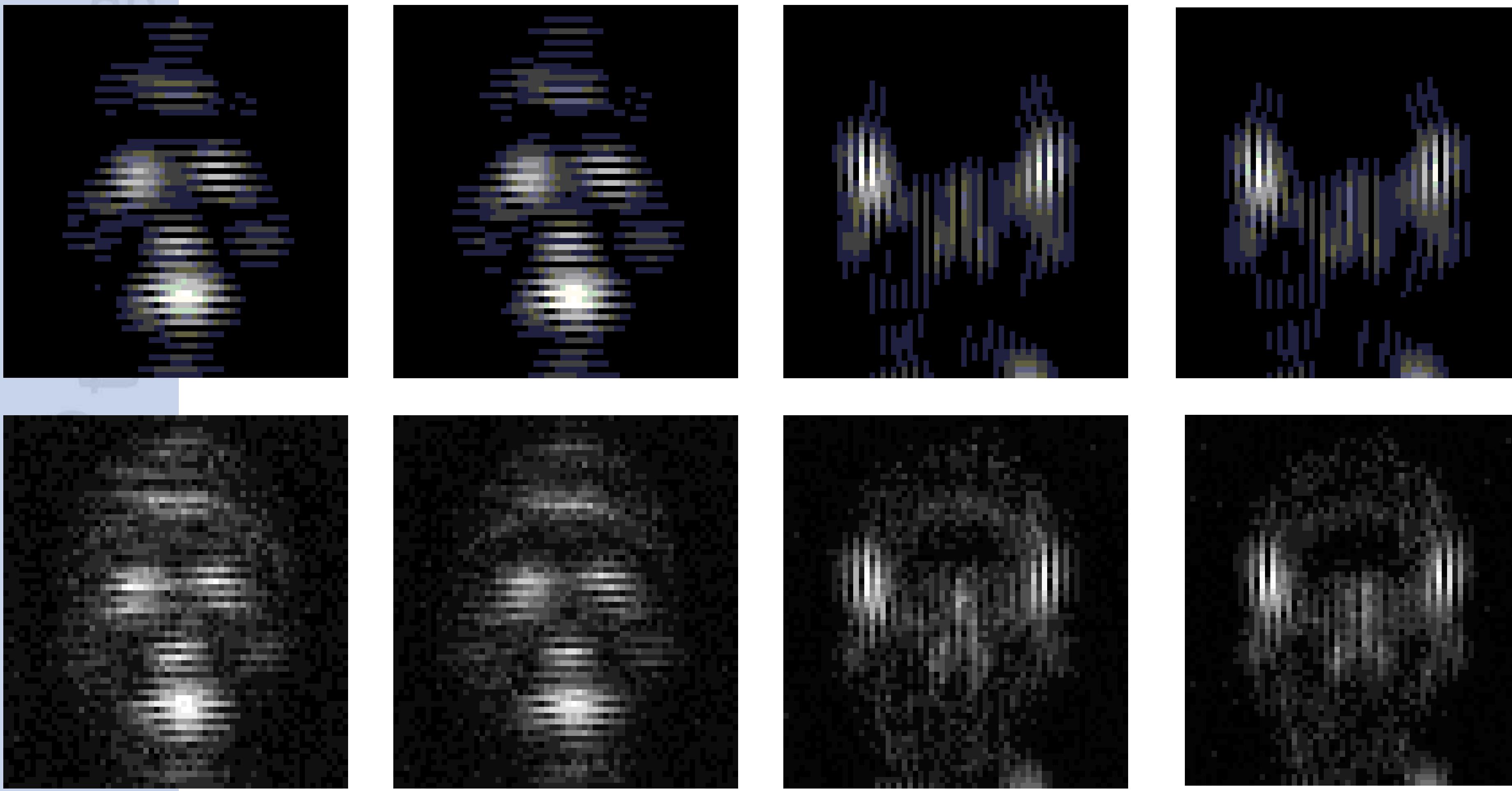
Results of a detector implementation

Gabor-Wavelet **measured profile**



- 256 Gradient detectors
- size of receptive field: 17 x 17 Pixel
- T=750ms @ 1ms Pulse-duration

Simulated Filter responses, T=750ms



Real 90° | Imaginary 90° | Real 0° | Imaginary 0°

The Head-Detector

Restriction

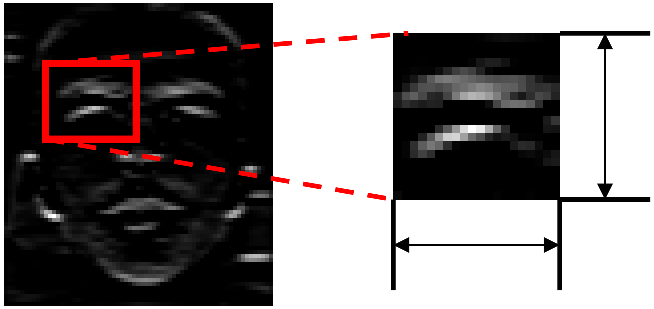
- single scale (keep eye-distance fixed)

Check for Robustness in Eye-Brow Zone

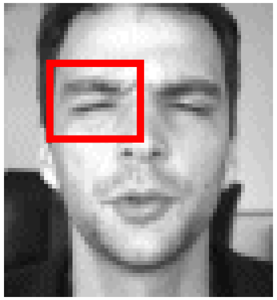
Reference Image

Filter Response, horizontal direction

region of interest



20x20 Pixel

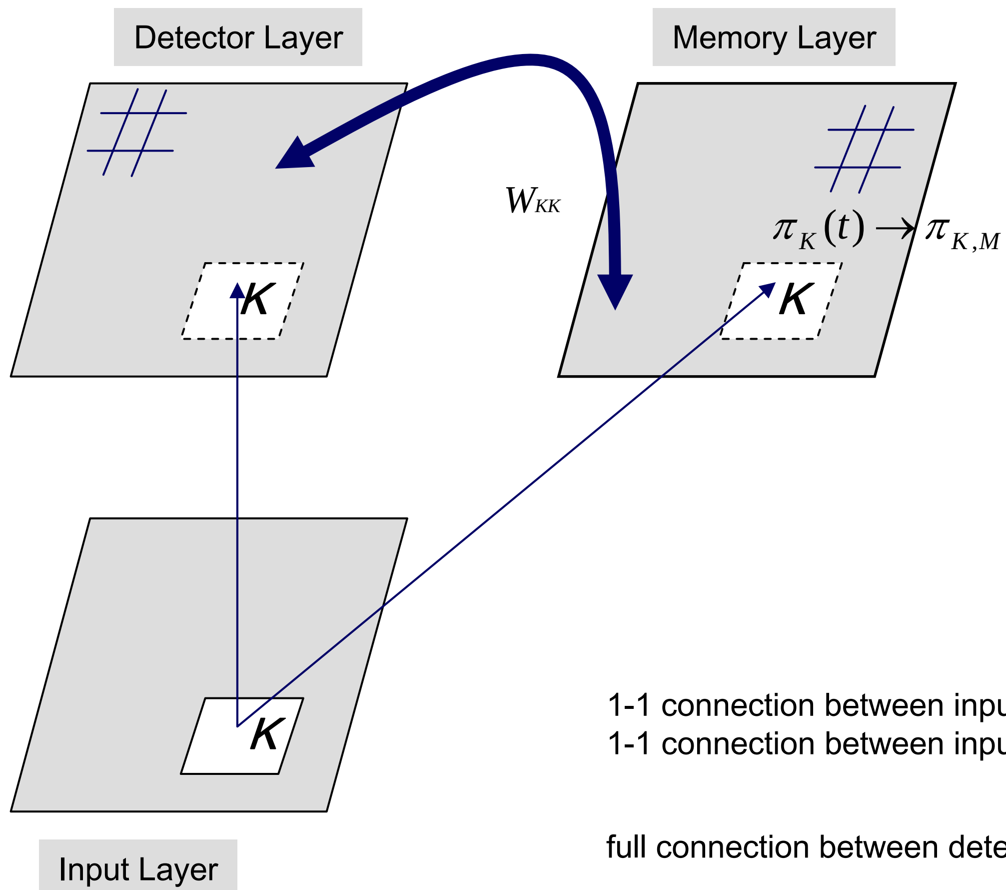


new eye-brow image

A simple memory (1) , 1 zone

Learning Phase

$$\dot{W}_{KL} = -\gamma W_{KL} + \mu \cdot \left(a_K - \frac{\theta}{2} \right) \cdot \chi(X_l) \cdot \exp\left(-(\pi_K(t) - \pi_L(t))^2 / \pi_L^2(t) \right)$$

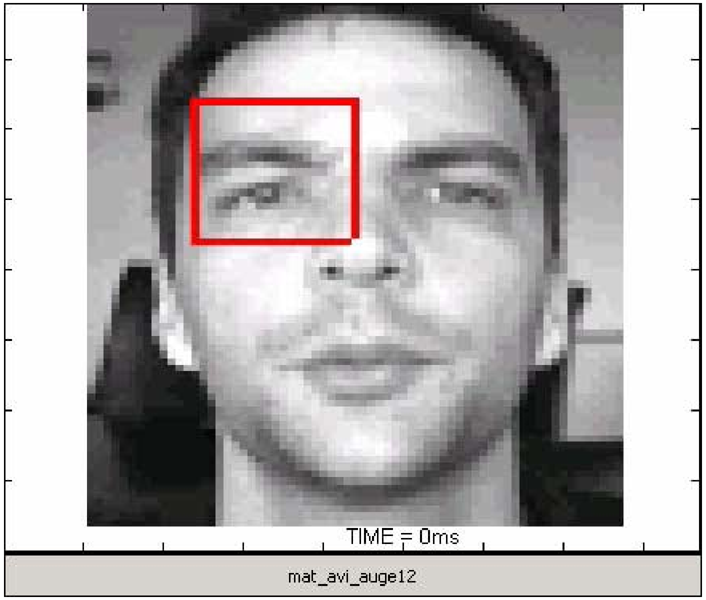


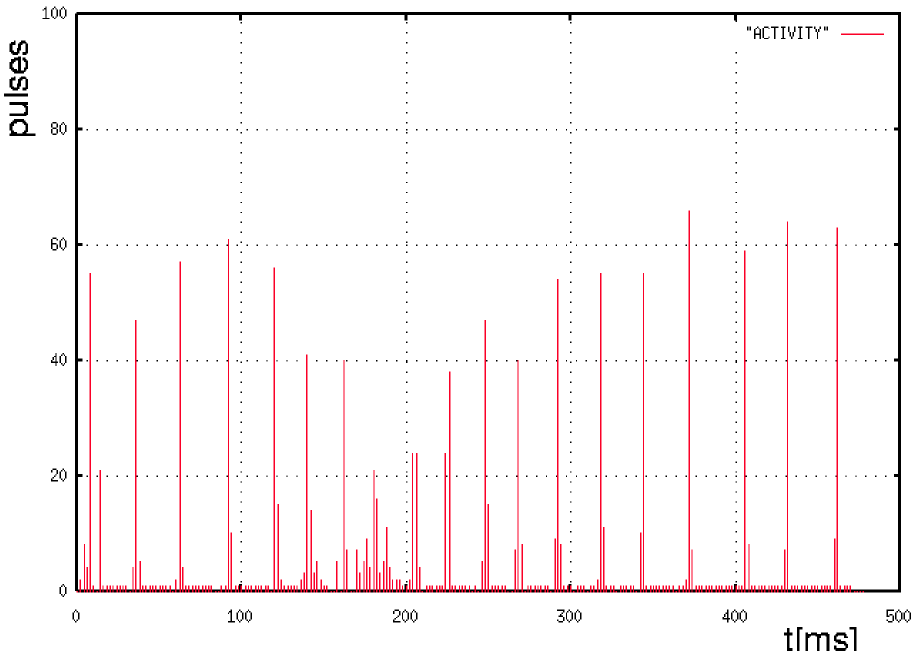
1-1 connection between input and detector layer
1-1 connection between input and memory layer

full connection between detector and memory layer

Experiment 1: learned image in input and memory

Activity (number of events), 2ms window

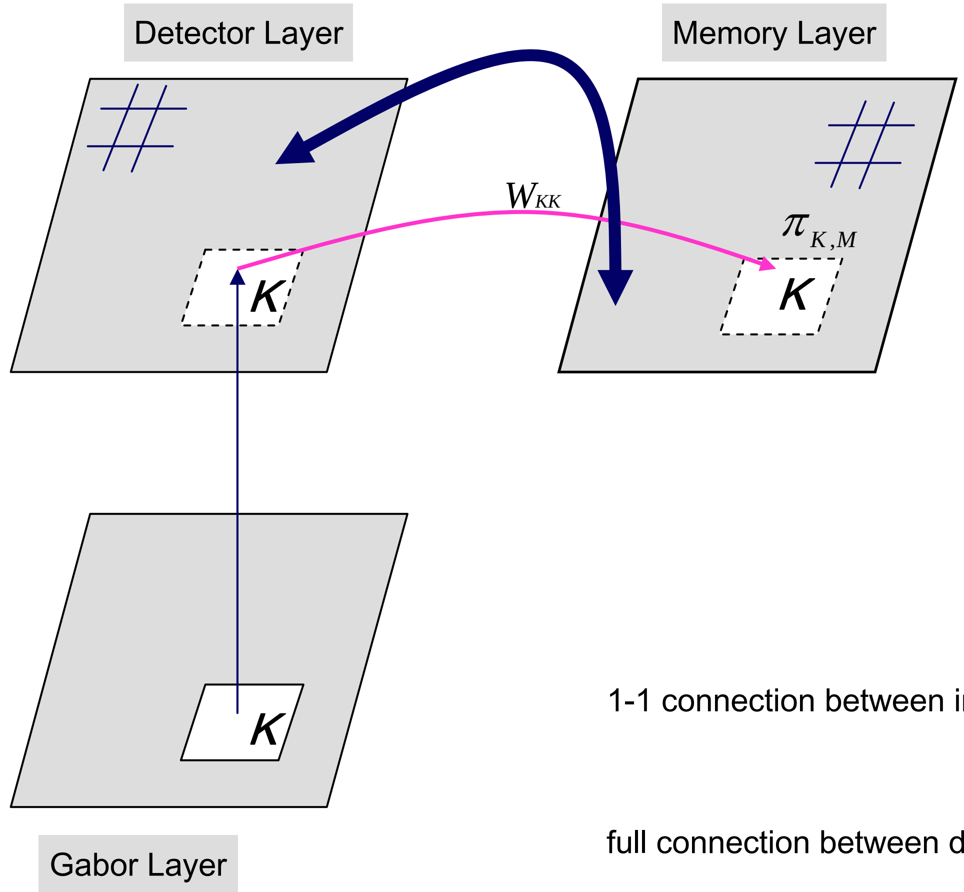




Pulse-patterns of input-layer

A simple memory (2), 1 Zone

Recognition Phase $$\dot{W}_{KL} = -\gamma W_{KL} + \mu \cdot \left(a_K - \frac{\theta}{2} \right) \cdot \chi(X_l) \cdot \exp\left(-\left(\pi_{K,M} - \pi_L(t) \right)^2 / \pi_L^2(t) \right)$$

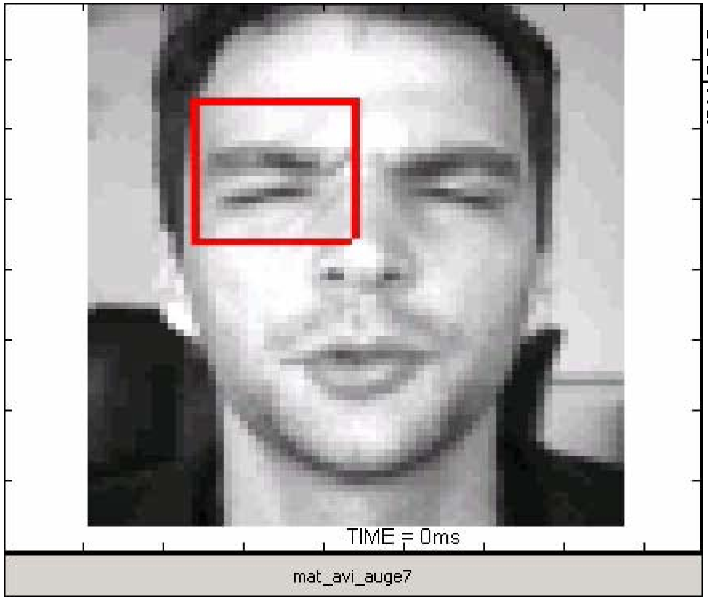


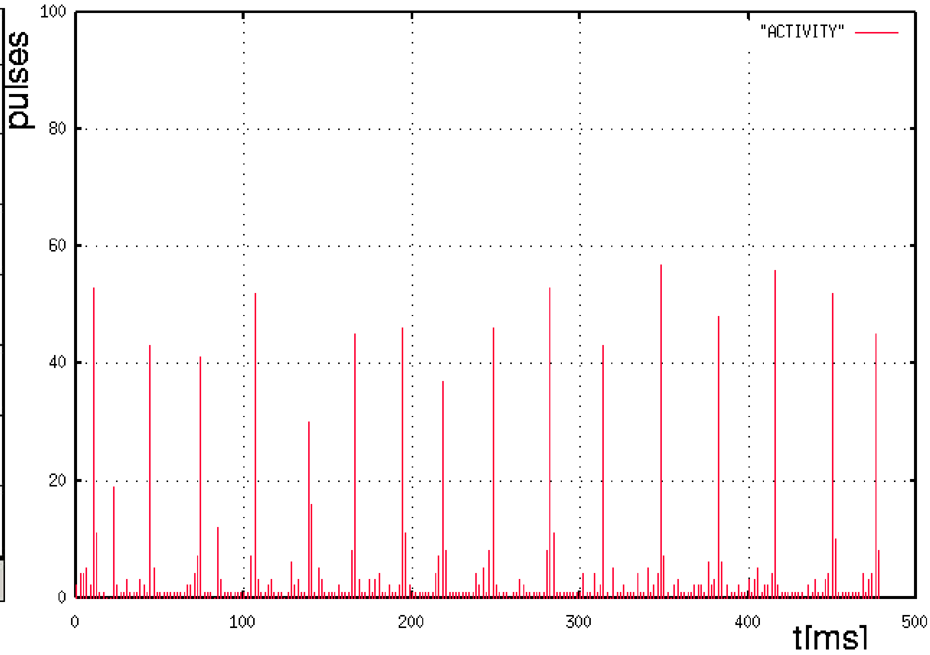
1-1 connection between input and detector layer

full connection between detector and memory layer

Experiment 3: recognition of non-learned eye-brow

Activity (number of events), 2ms window

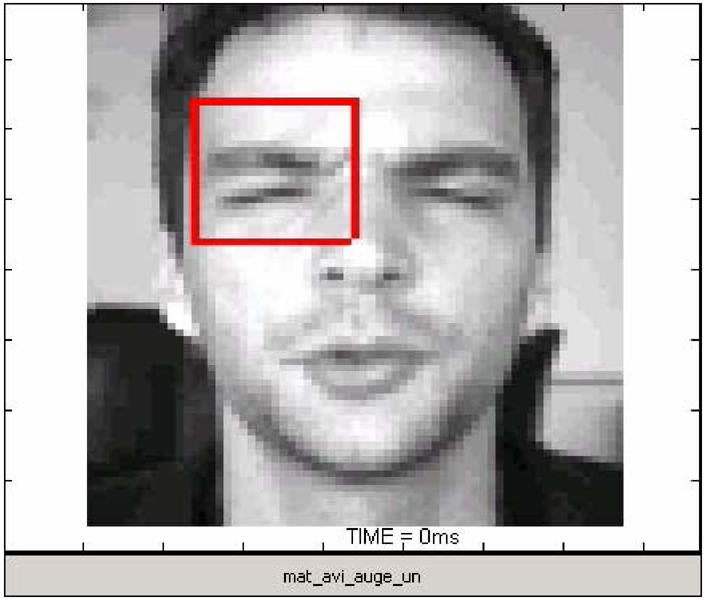


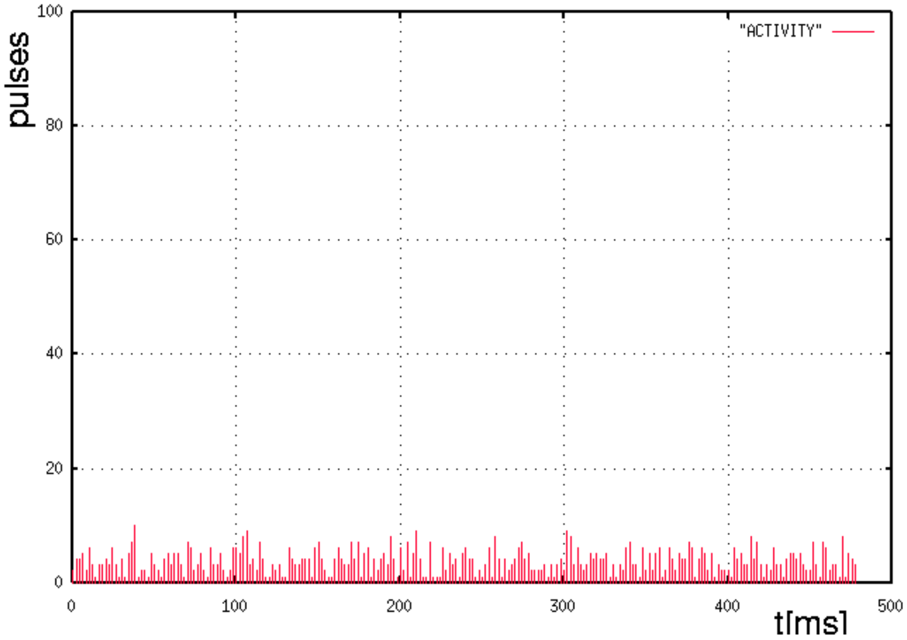


Pulse-patterns of input-layer

Experiment 2: Isolated neurons

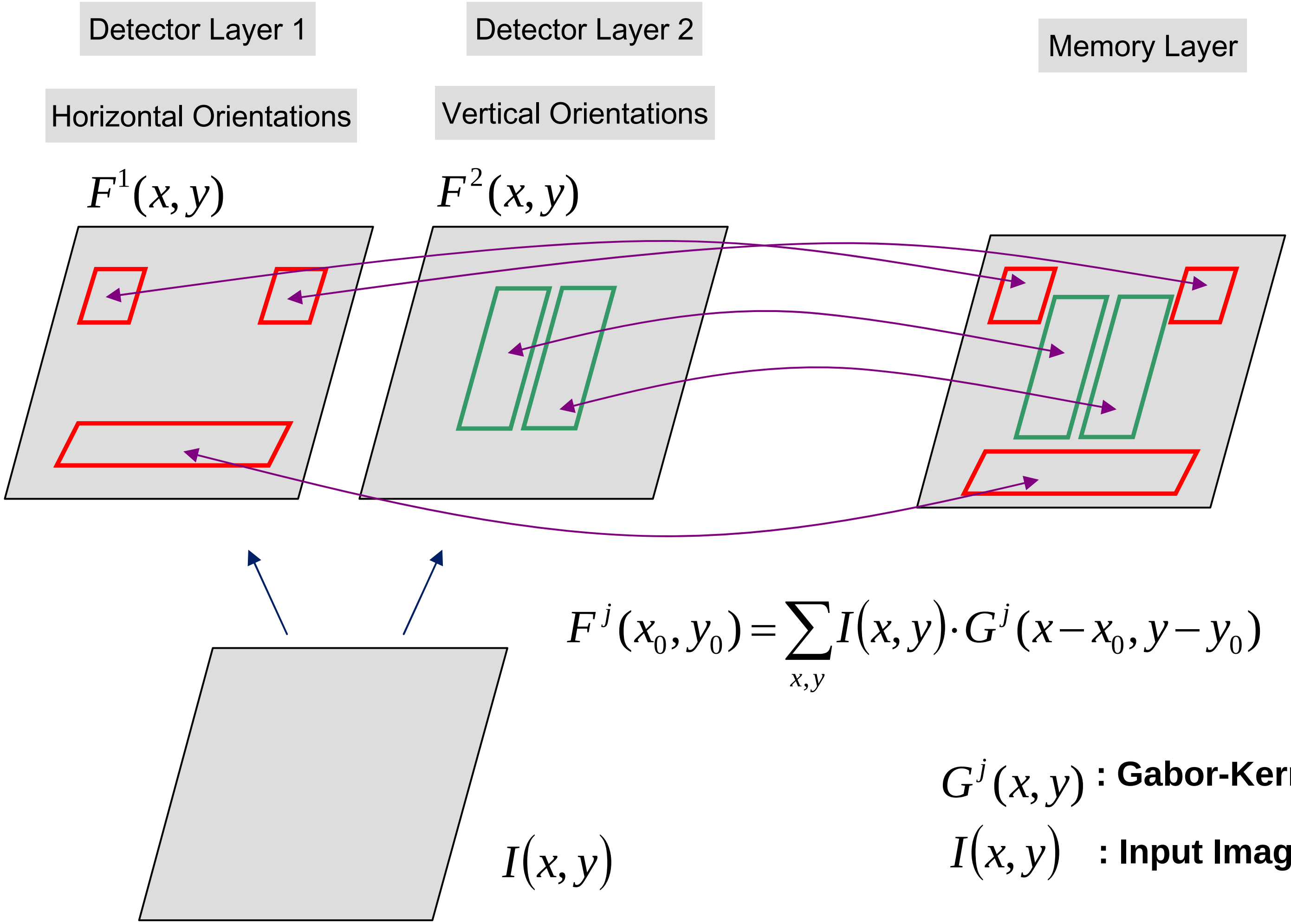
Activity (number of events), 2ms window





Pulse-patterns of input-layer

Zone-Architecture I

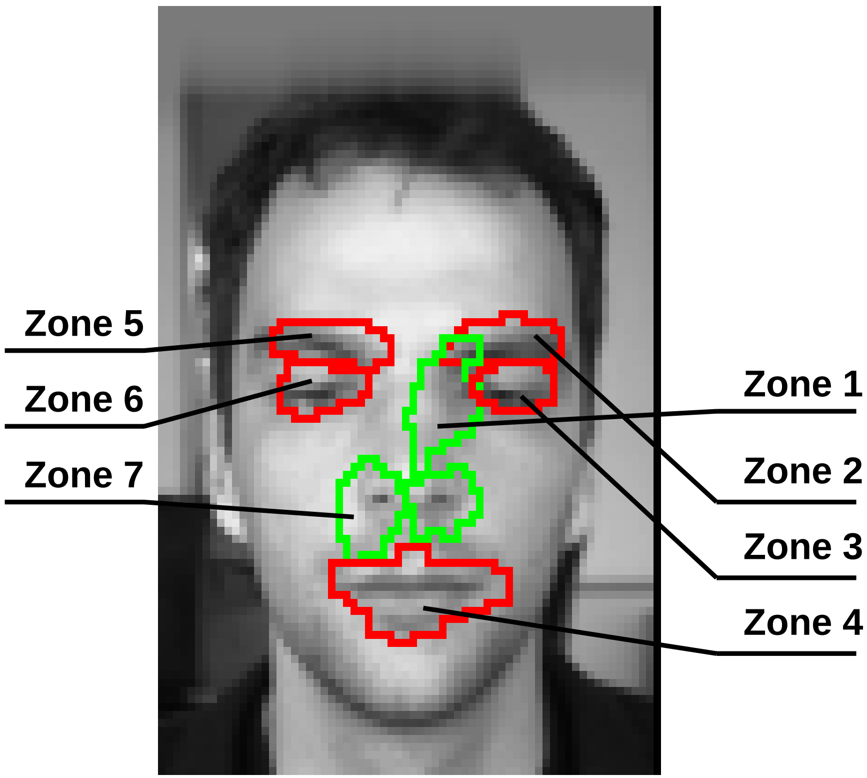


$$F^j(x_0,y_0)=\sum_{x,y} I(x,y)\cdot G^j(x-x_0,y-y_0)$$

$G^j(x,y)$ **: Gabor-Kernel**

$I(x,y)$ **: Input Image**

Zone-Architecture II



Zuordnung: Zonen zu Bildregionen


: Zone für Gabor-Wavlet mit horizontaler Orientierung

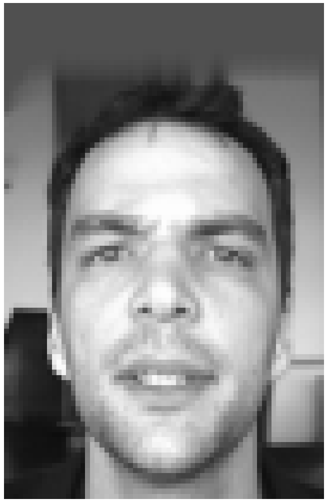

: Zone für Gabor-Wavlet mit vertikaler Orientierung

Reference-Image and Test-Images

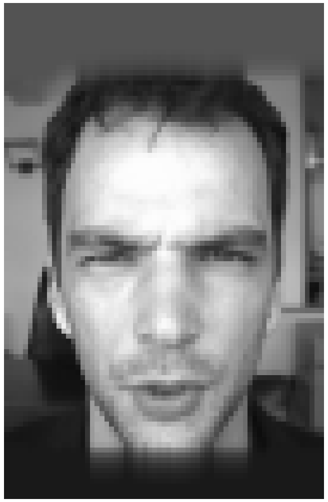
Reference-Image:

Test-Images:

Face 0001



Face 0011



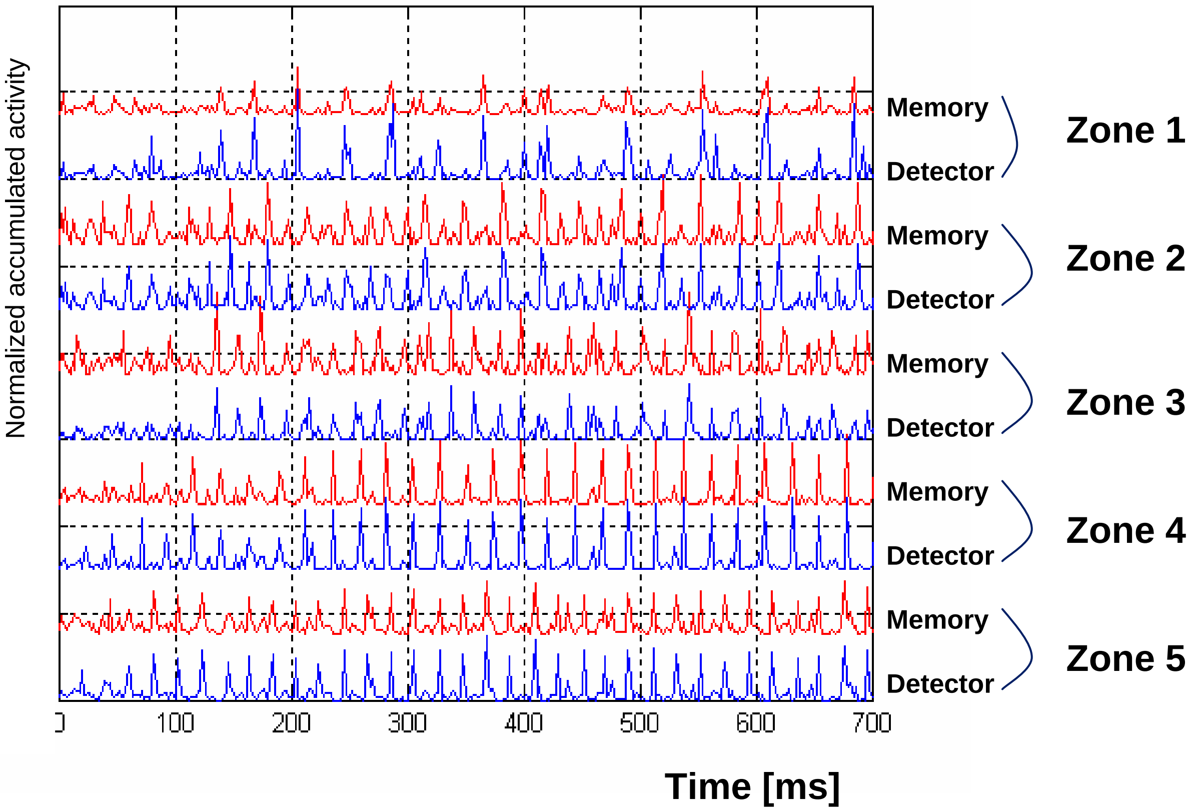
Face 0014

Face 0001

Activity-Diagram

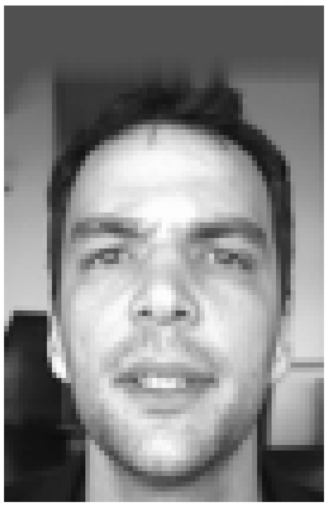
Video Clip

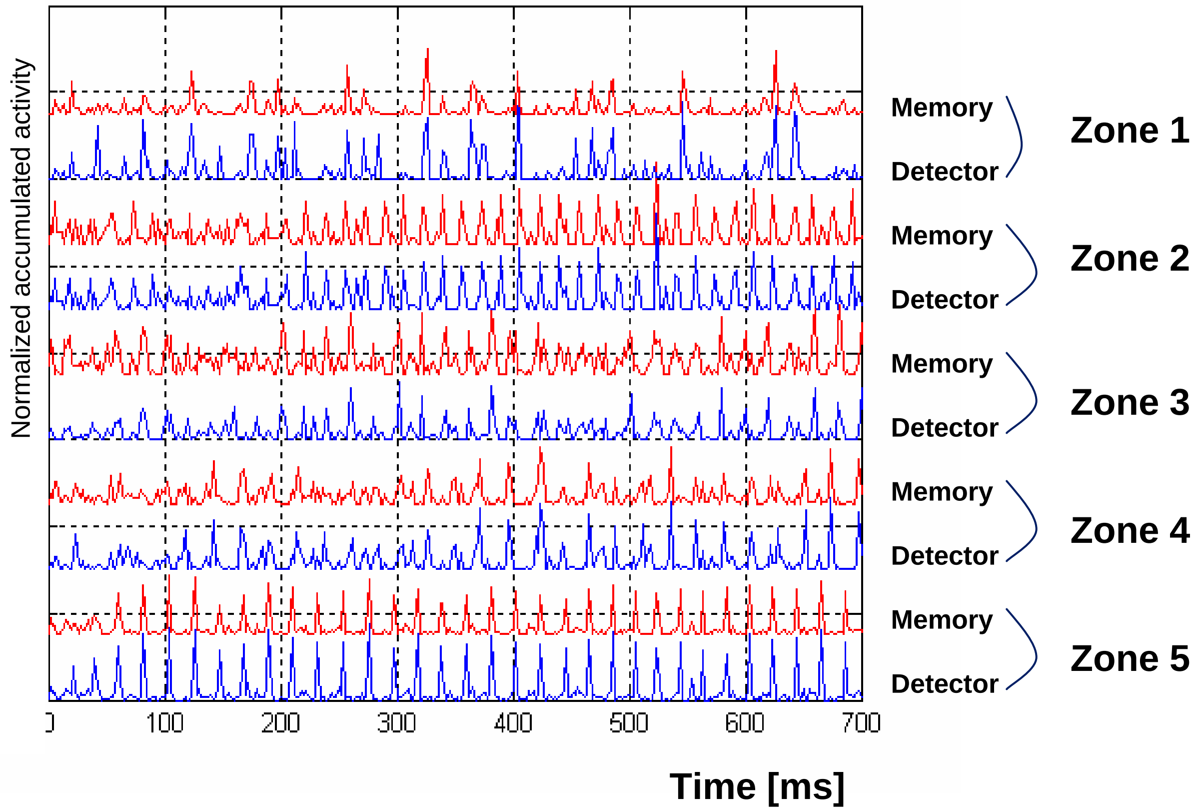
Video Clip



Face 0011

Activity-Diagram



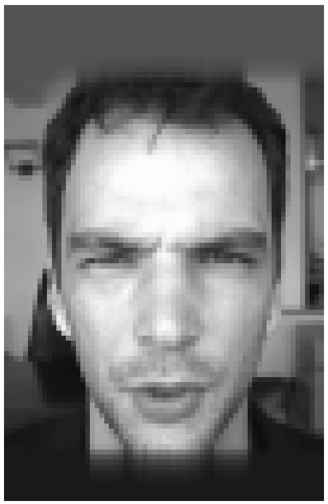


Video Clip

Video Clip

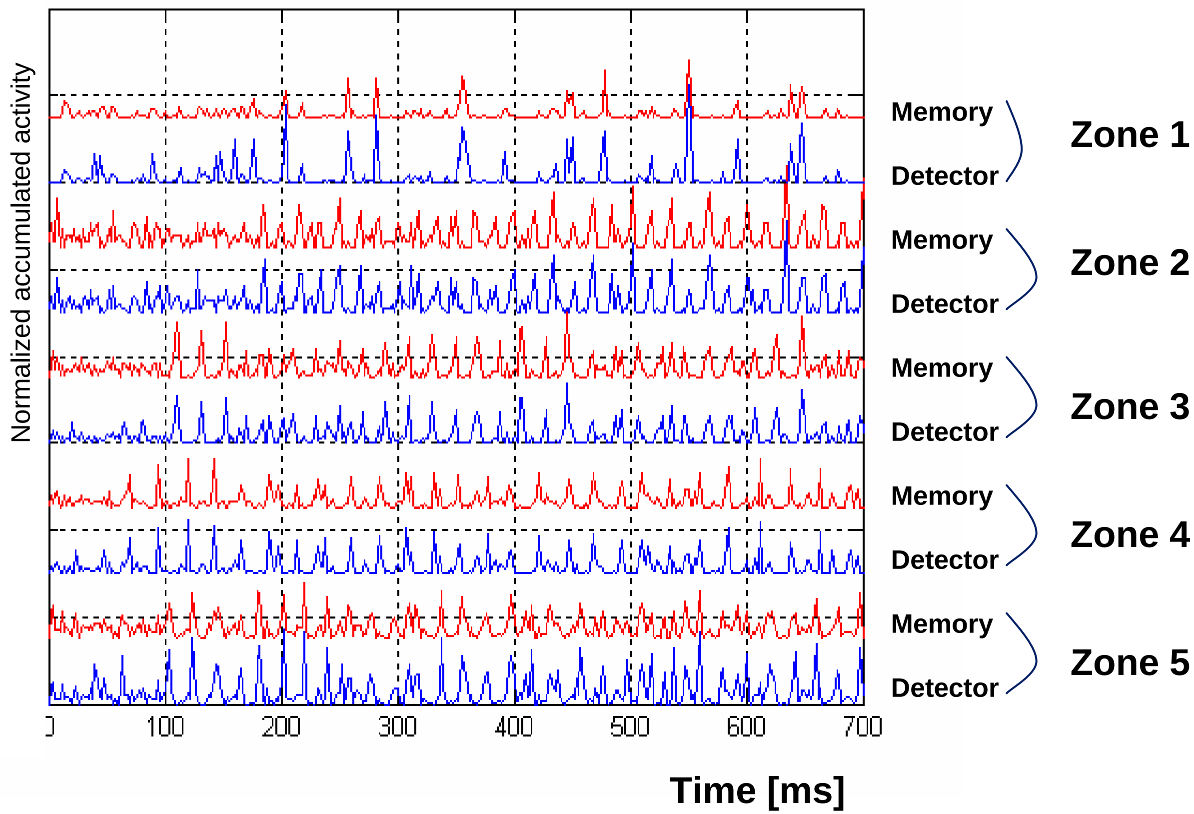
Face 0014

Activity-Diagram



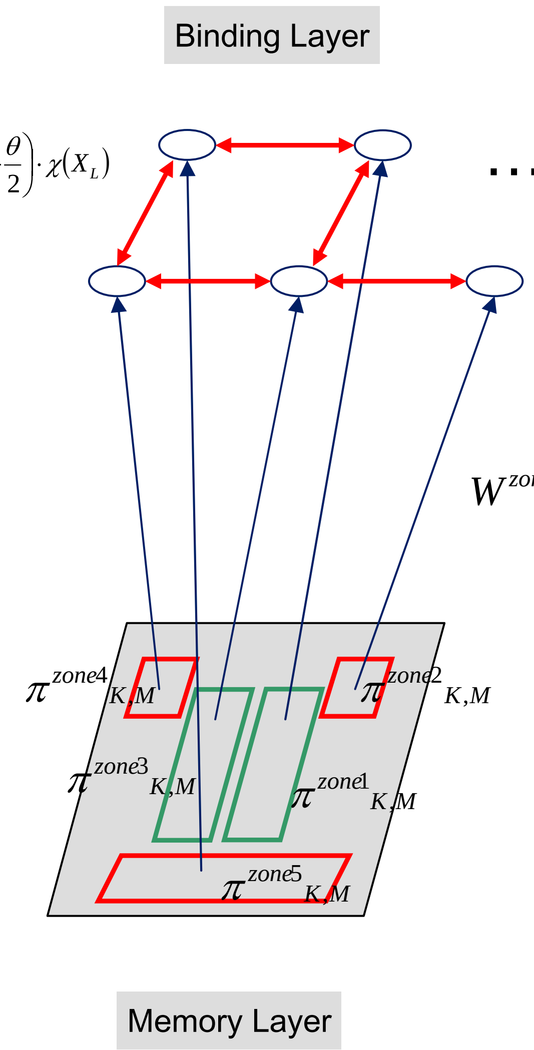
Video Clip

Video Clip

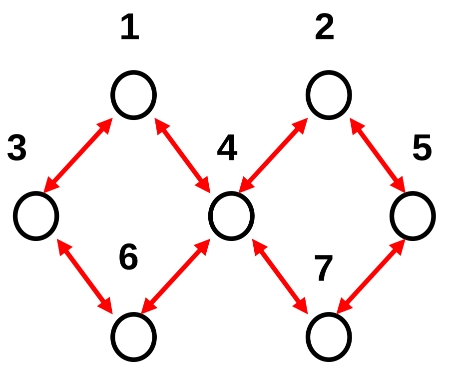


Binding of zones by synchrony

$$\dot{W}_{KL} = -\gamma W_{KL} + \mu \cdot \left(a_K - \frac{\theta}{2} \right) \cdot \chi(X_L)$$

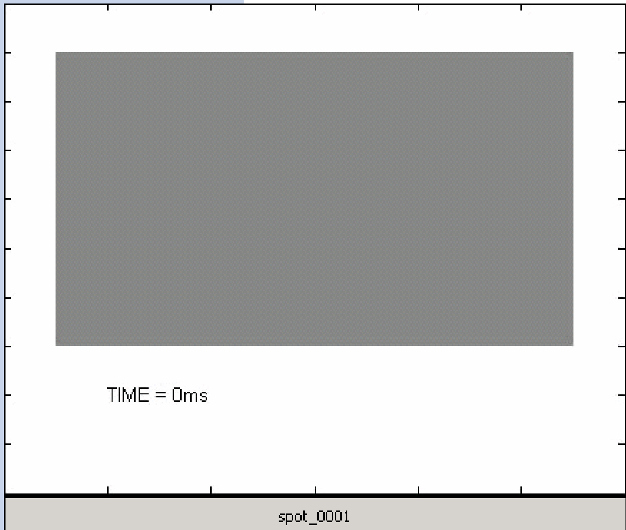


$$W^{zone\,i} \propto 1/\pi^{zone\,i}{}_{K,M}$$



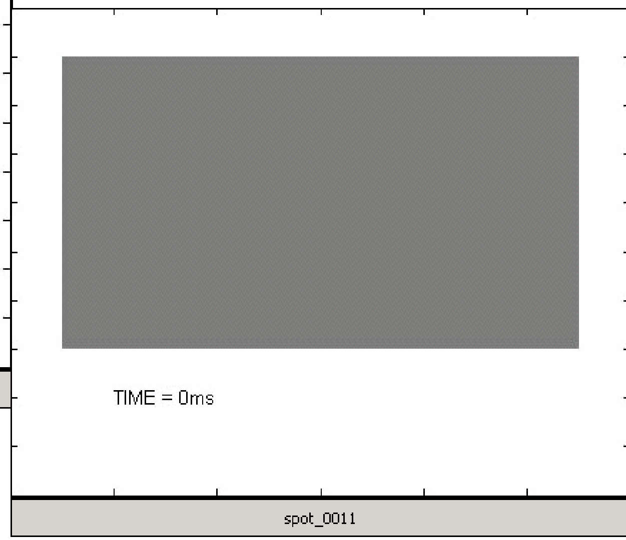
Zuordnung: Zonen zu Neuronen des Spotdetektors zur Bindung

Results



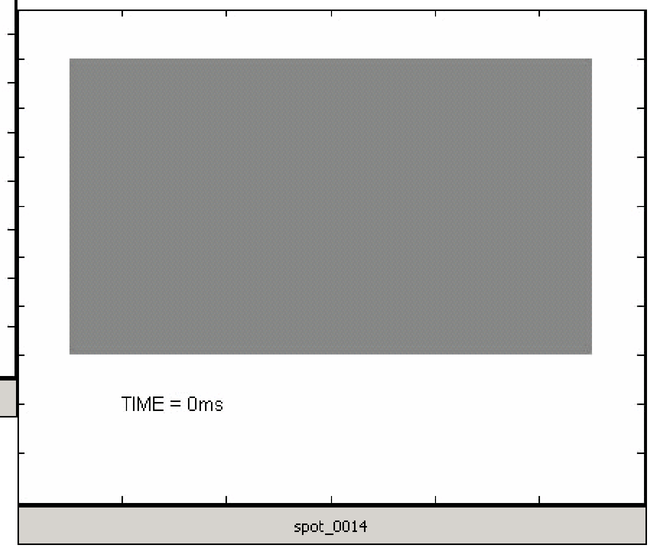
~ 40ms

Spot_0001



~ 40ms

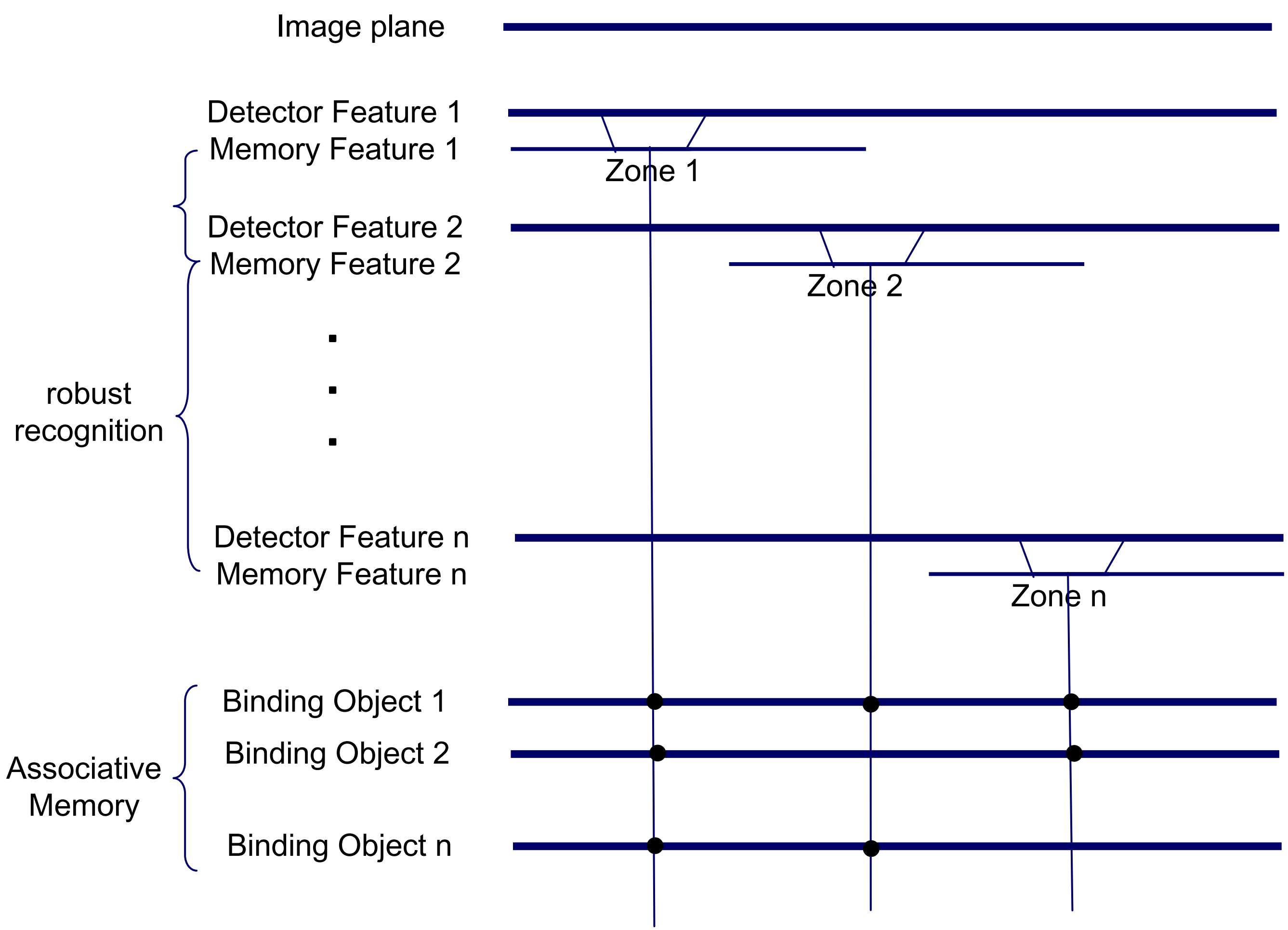
Spot_0011



~ 40ms

Spot_0014

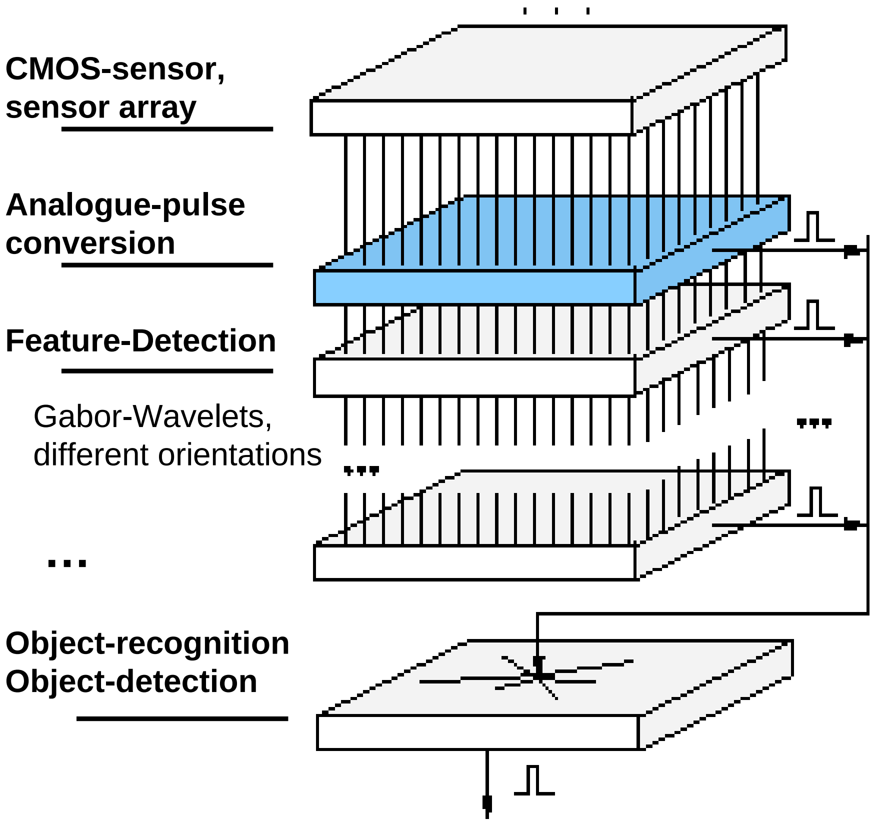
Column Architecture



The vision: a 3D-Vision-Cube

The Vision-Cube

- 3D-stacking-architecture
- Low-power
- Real time capabilities
- Integration of sensors and information processing
- Distributes layers of information processing to layers of the stack
- Solves problem of connectivity



Design of a testchip for the „Synchrony detector“, Base-Chip for the 3D-Stack

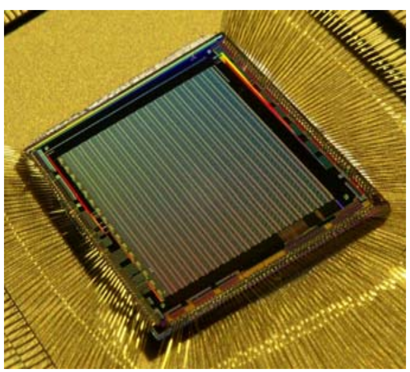
Infineon 130nm CMOS-Technology

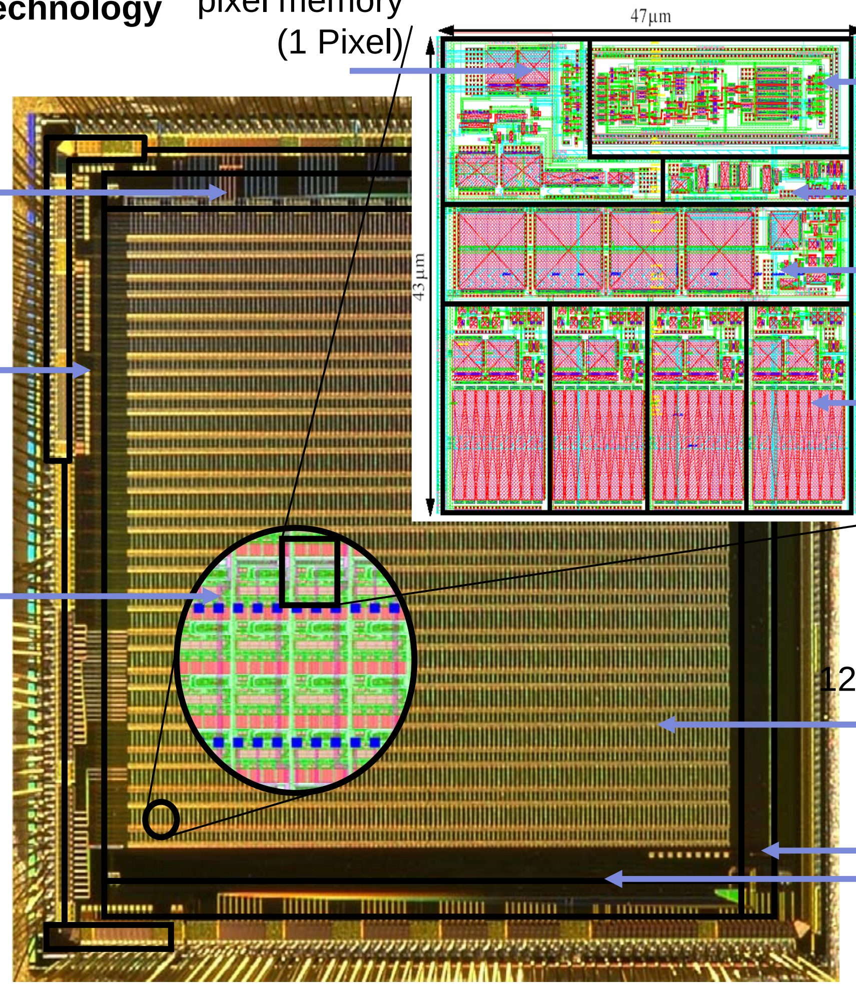
pixel memory (1 Pixel)

testcircuits for 3D-interconnects

3D-vias for supply and digital control signals

rows of 3D-vias for layer-to-layer signal distribution





local AER-subcircuit

Test circuit

Integrate-and-Fire-Neuron

adaptive synapses

layout of 1 neuron

array of 128 x 128 neurons, 64k synapses

control circuit

AER-encoder-circuit

Power consumption: 3mW @1.5V (analog) , 40-250mW @1.5V (digital)

Size: 7.6mm x 7.8mm

Gabor-Feature-Detector chip (layout) including a pulse router for the 3D-integration

Infineon 130nm CMOS-Technology

Array of 128x128 (64k) processing elements for pulse processing and -routing

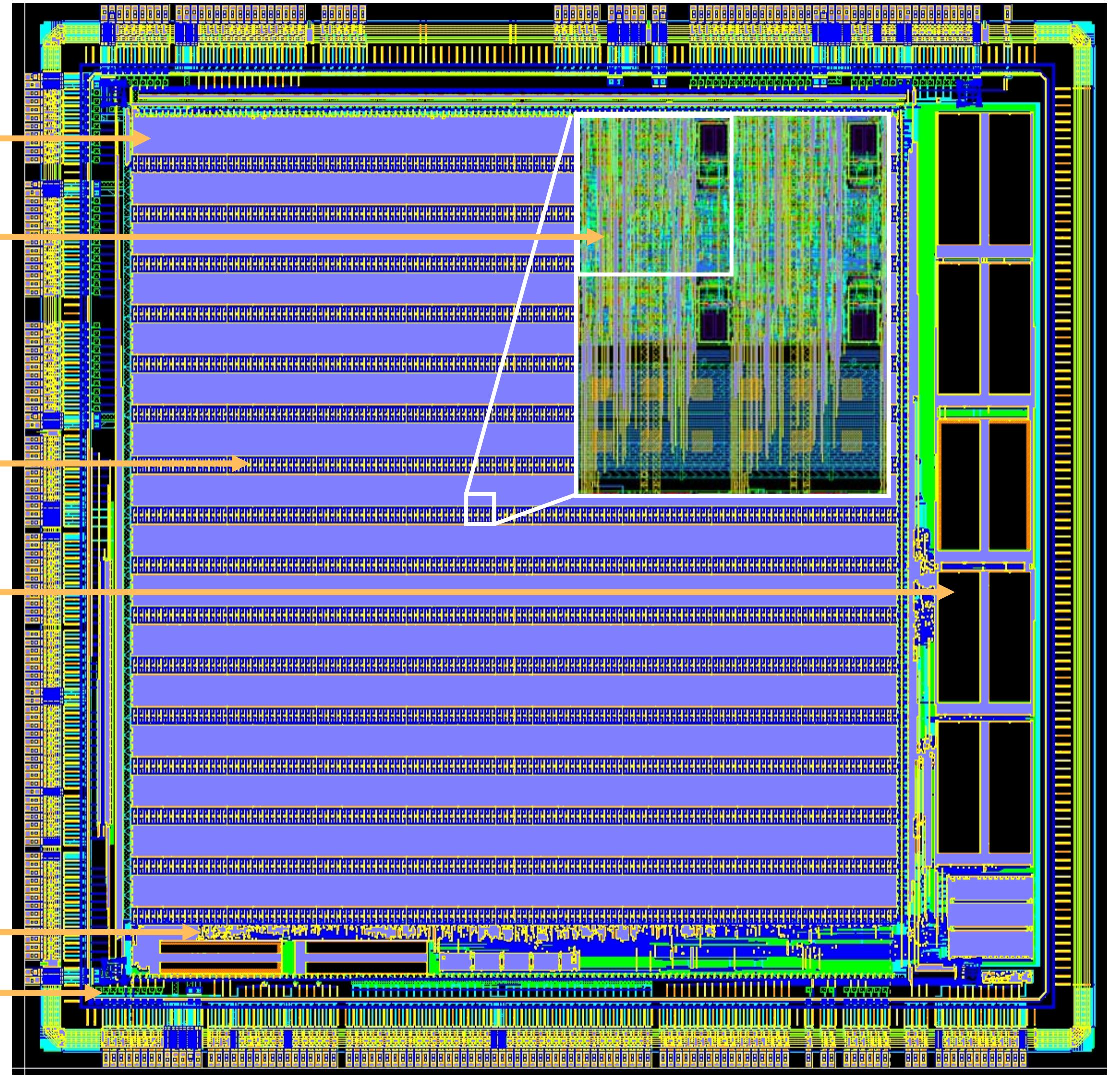
Processing element:
- photo-Detector
- pulse-processing (gradient detection)
- dynamic routing of pulses

3D- wiring channel for vertical signal distribution

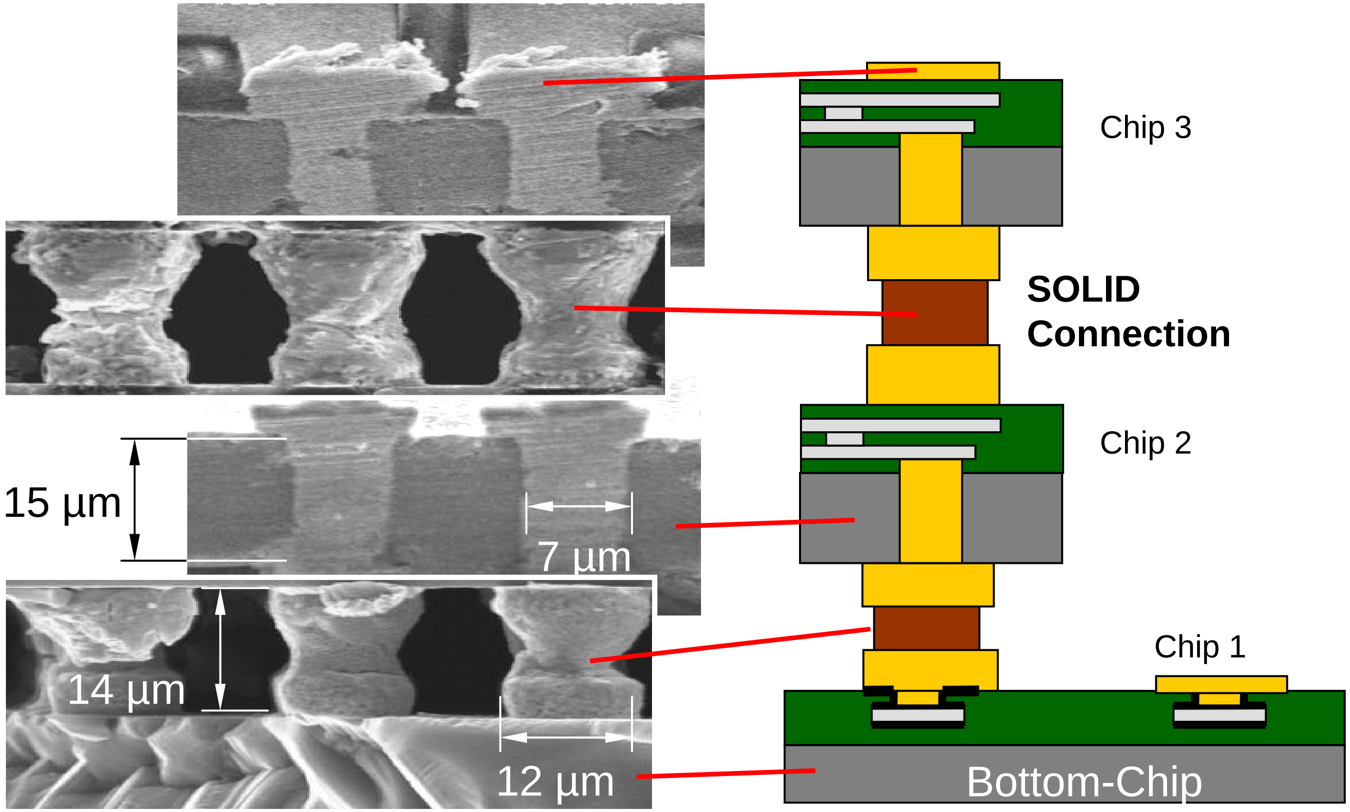
SRAM for storing routing information

Digital macro:
- routing circuit
- configuration
- AER-circuit (event based)

3D- wiring for power supply and control signals

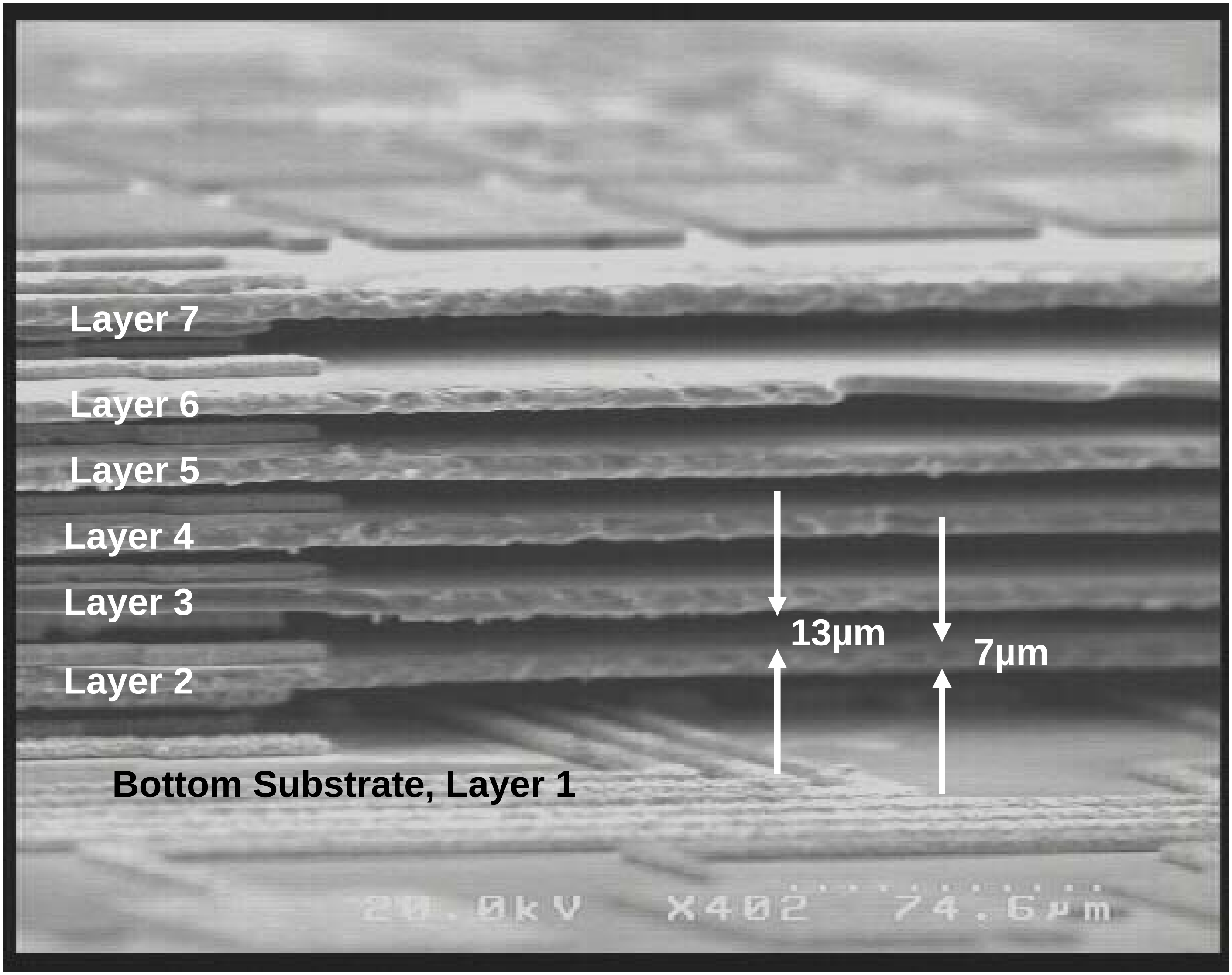


3D-Stacking



15 µm
7 µm
14 µm
12 µm
Chip 3
SOLID
Connection
Chip 2
Chip 1
Bottom-Chip

Real 3D !!



Layer 7
Layer 6
Layer 5
Layer 4
Layer 3
Layer 2
Bottom Substrate, Layer 1
13µm
7µm
20.0kV X402 74.6µm

Conclusion

- IAF neurons, adaptive synapses, only
- network built for
  -- Gabor wavelet based feature cascade
  -- memory
  -- comparison of memory and detector plane
- synchrony of neurons indicative for
  -- robust recognition of memory feature at detector plane (elastic matching)
  -- binding of features as object
- built in 130 nm CMOS
  -- synchrony detector
  -- Gabor wavelet detector
  -- 3 D stack of 7 silicon chips