Real Time Vision

Roland Köberle

Department of Physics/DipteraLab - USP-São Carlos, Brasil

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Experiments: I. Zuccoloto

The processing path

- How to reconstruct the external world - *in particular how to understand what I am talking about* - from a sequence of `identical electrical pulses` propagating information in your cortex?
- External world $\rightarrow$ Sensory Sistems $\rightarrow$ Processing Stages *(Thalamic Nuclei)*$\rightarrow$ Cortex $\rightarrow$ Motor System etc.
- Example: Visual System

  Reconstruct scenes in REAL TIME

- Problems: ....∞.....

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Idiosyncrasies of the brain/visual system - only 2!

1. Our Brain: is driven to find

   ORDER in **CHAOS.**

   - *Could this be the defining property of our brain!?*
   - William James claimed that *the sense of sameness is the very keel and backbone of our thinking*. In that case the computational goal of V1 may turn out to be closer to that of the cerebral cortex as a whole than has been generally recognized[Barlow2010].

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Visual Reconstruction: difficulties

1. How to reconstruct a **3D** scene from **2D** informations?
   - This is an *ill* posed problem $\rightarrow$
   - We need to use *inferences*.
2. Even as signals are decoded (*largely unconsciously*) in real time, we use inference based on experience acquired in the past!
3. Neither the visual system is obsessed with [illegible] problems etc.

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2D information

2D information should include:

1. Information about surfaces and their depth (*Marr D2.5*)
2. Location and boundaries of the main objects in the scene - albedos, light sources
3. Grouping of objects etc
4. ..... Examples .... [Mumford:2007]

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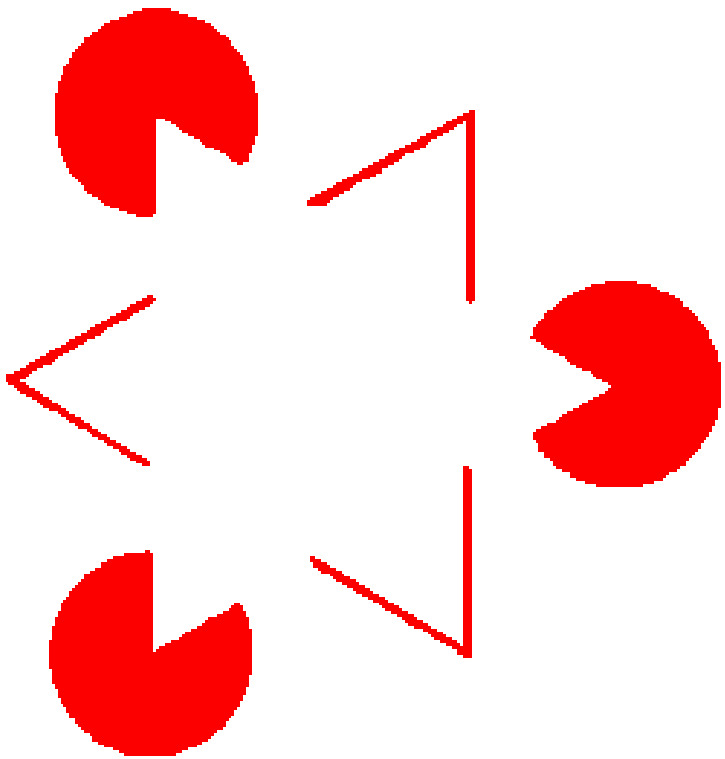
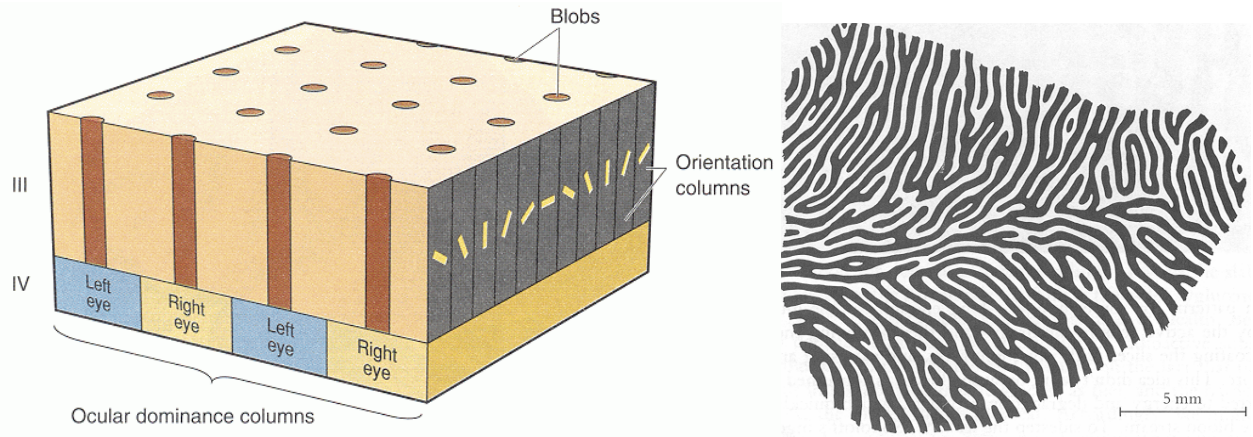
Kaniza2



Extracting Discontinuities: Columns and Ocular Dominance



Retinotopic representations preserve neighbourhoods $\rightarrow$ allow us to maintain continuity.

Simplifications are essential - WHICH ONES???

- Problems with depth, occlusion and continuity are terrifying obstacles to overcome in 3D scene reconstruction.
  Let us simplify our life!!
- Compare the treatment of the Ising-model in the presence of a magnetic field in one and two dimensions!!

  $\Rightarrow$
- Let us investigate neuronstrength on time

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Find the free fall analogy

1. Which properties are important and which ones we can neglect?
2. Once importance is decided, how can it be validated? How can we measure it?

- Assume: *Positions of edges are the main features of the scene.*

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Designing experiments: *are discontinuities truly that important?*

1. Generate stimuli $s_0(t)$ with discontinuities only.
   - Measure the system's response $R_0(t)$ to $s_0(t)$.
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2. Measure the response to a more complete stimulus $s_1(t)$, but which maintains all the discontinuities of $s_0(t)$.
3. Compare the information I_0 and I_1.
4. Add noise to investigate the stability of the response.

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GO TO ONE DIMENSION: *THE FLY*

Coding Precision

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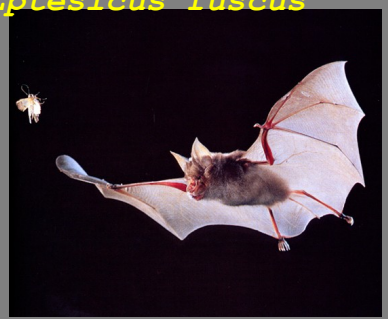
Eptesicus fuscus

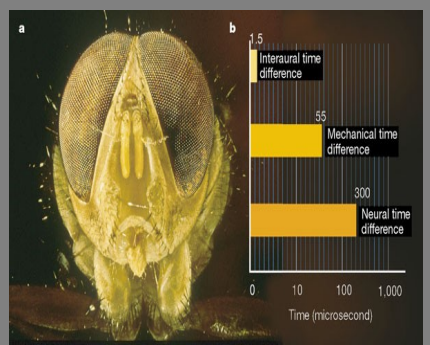


Simmons, Ferragamo e Sanderson, J Comp Physiol, 189,693-702,2003.

Temporal Precison:

Eptesicus fuscus: 10ns
Ormia ochracea: 50ns
Eigenmannia: 100ns

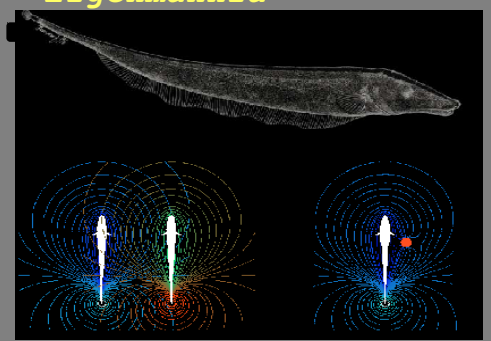
Ormia ochracea



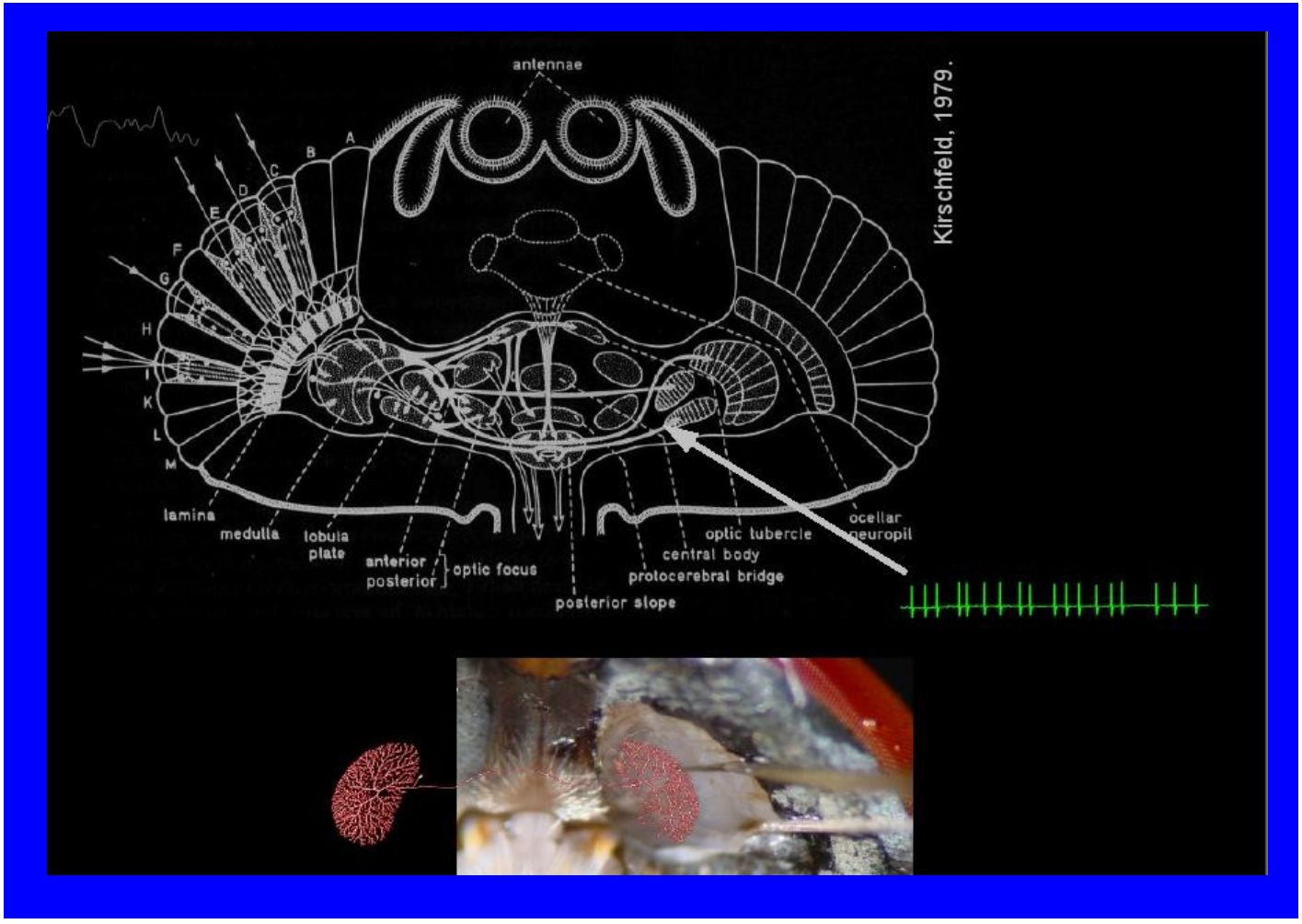
Rose e Heilingenberg, Nature,318,178-180,1985.

Mason,Oshinsky e Hoy, Nature,410,686-690,2001.

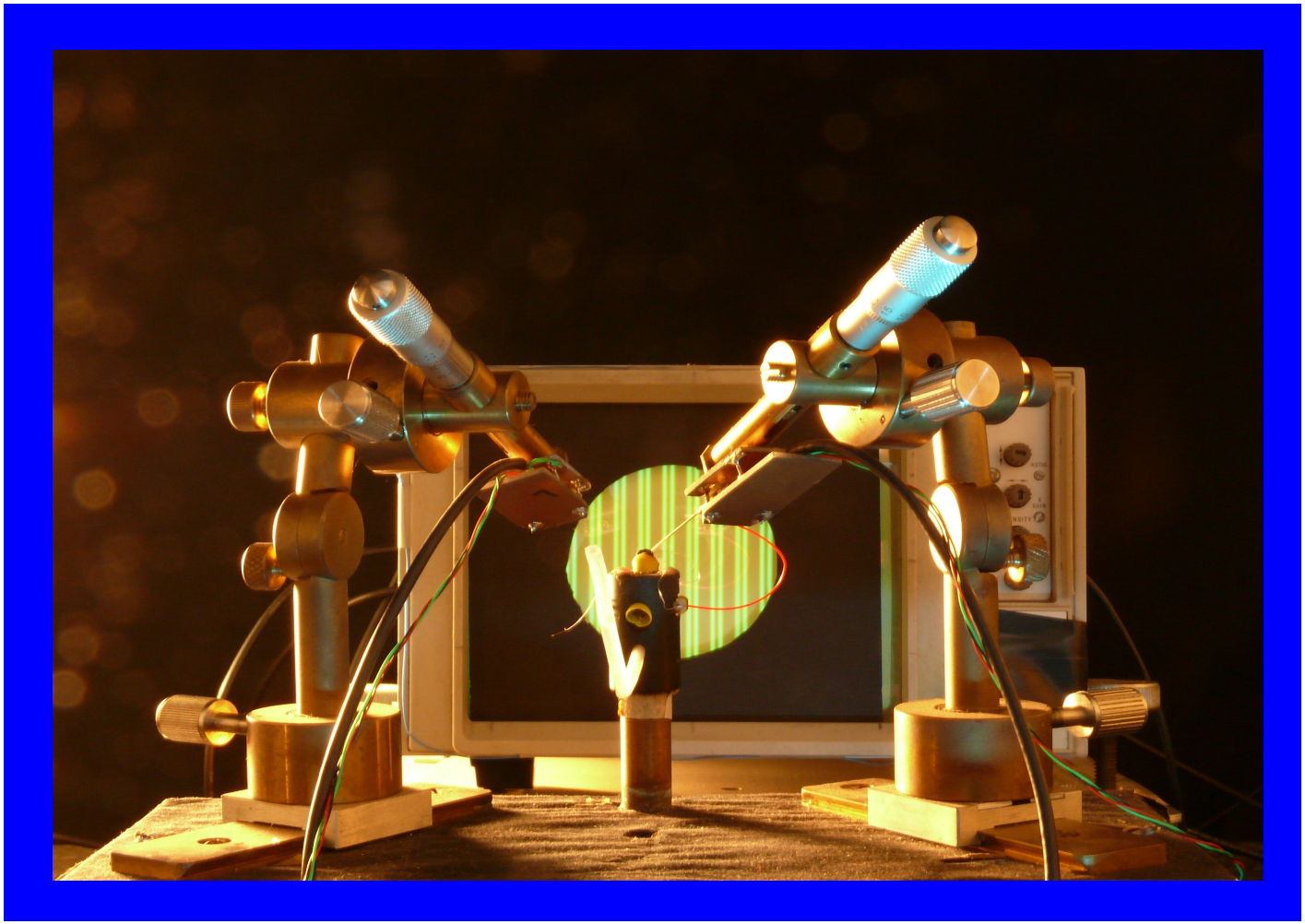
Eigenmannia



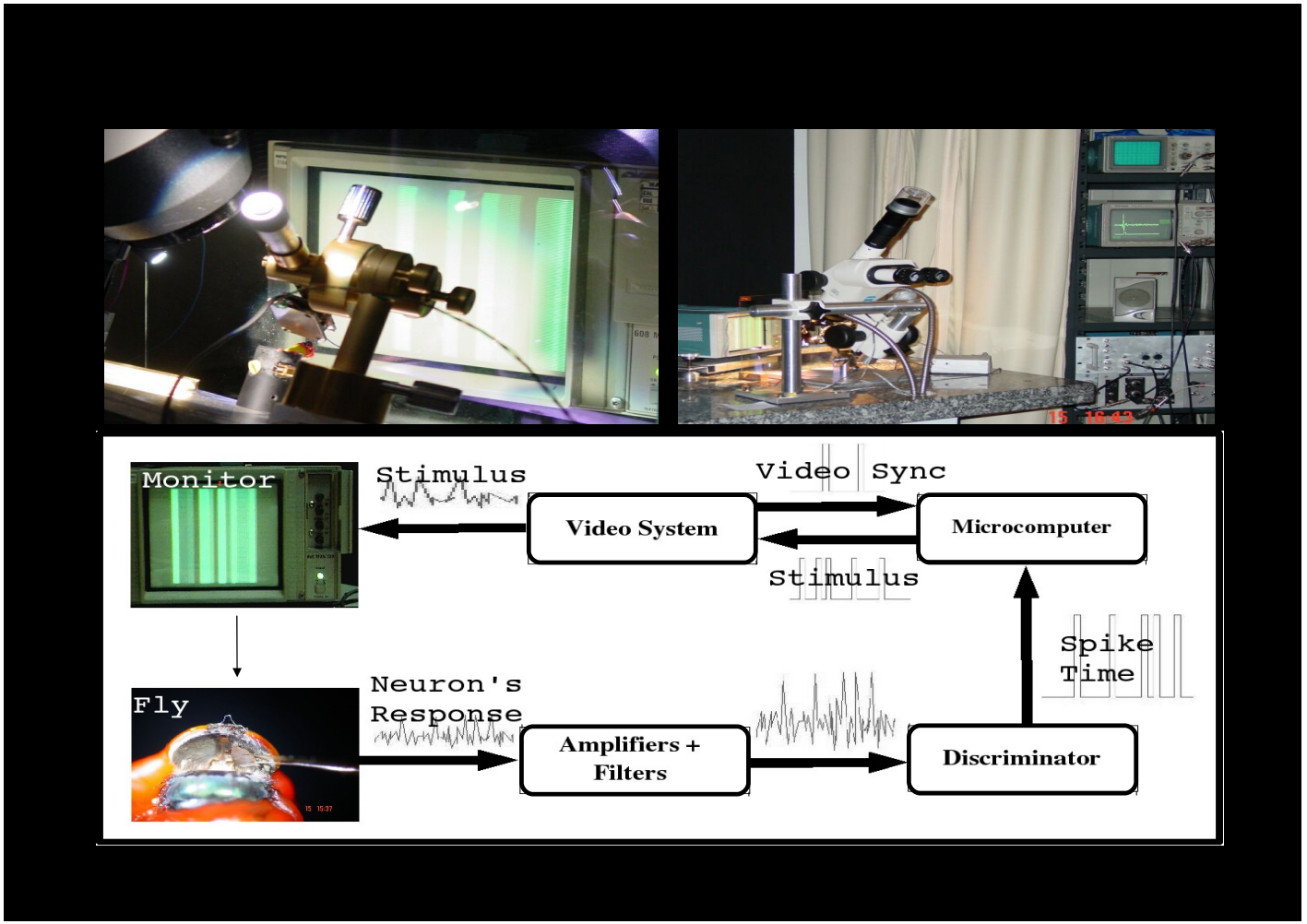
The fly's visual system



Recording from left and right H1



Experimental Setup



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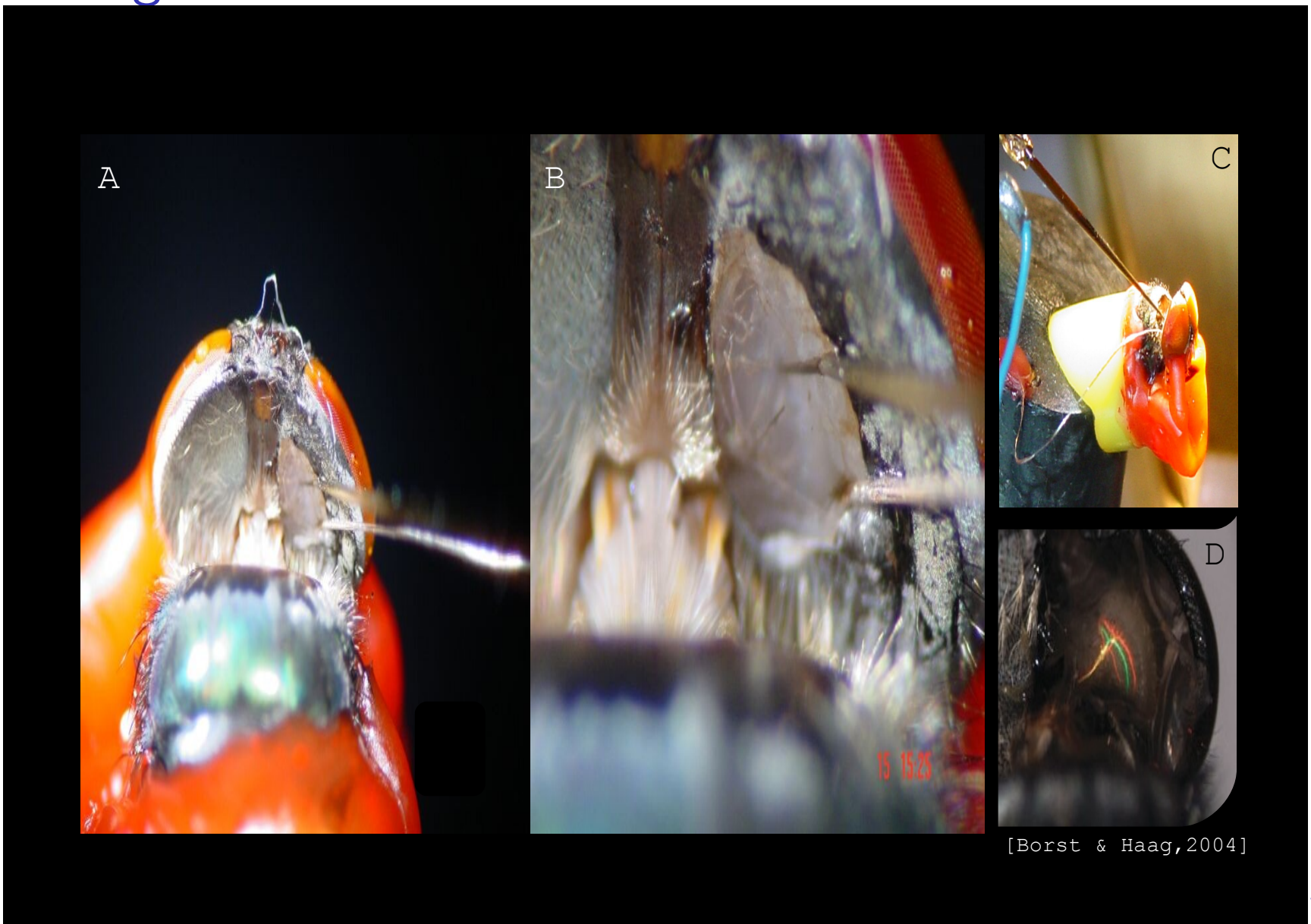
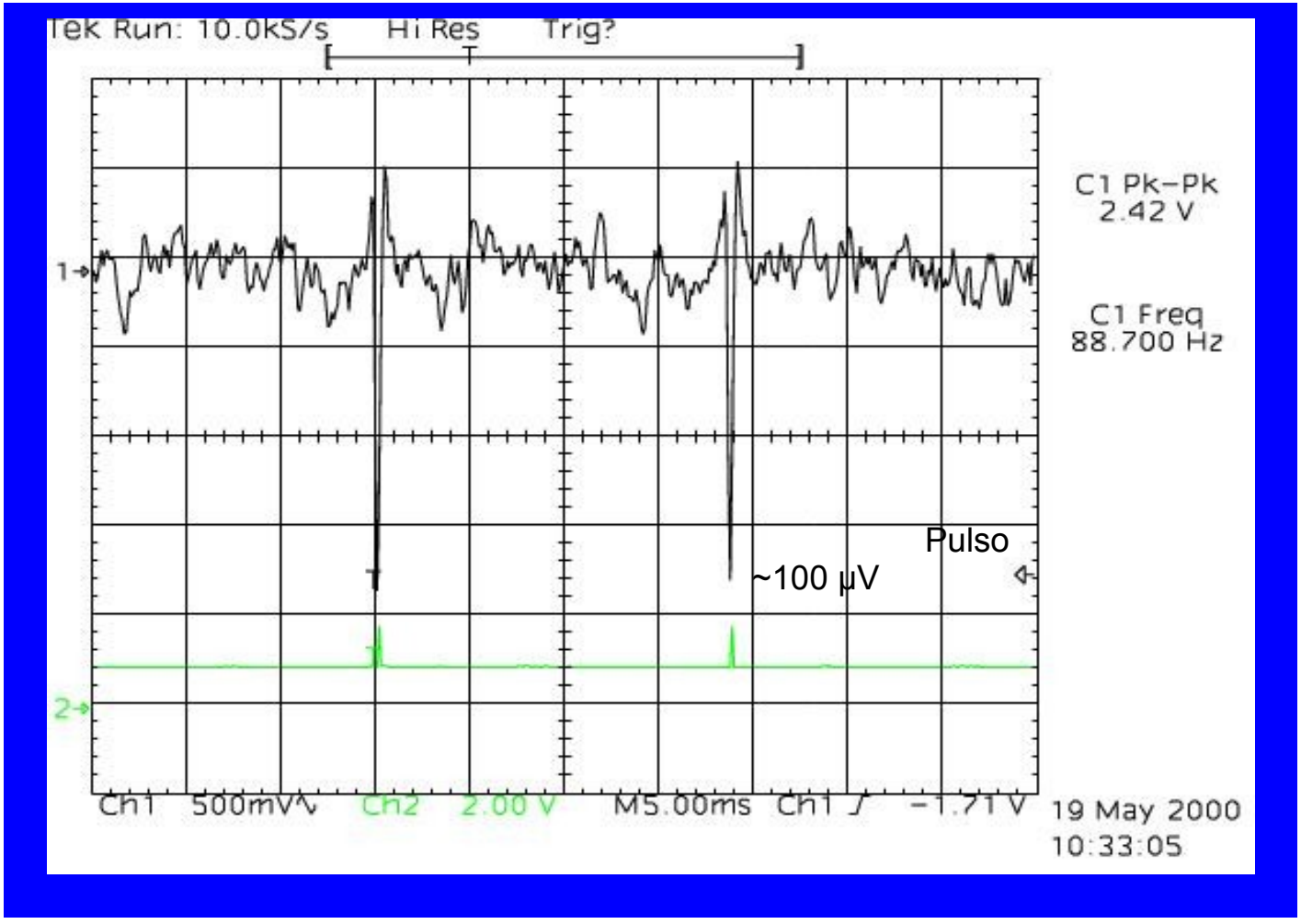
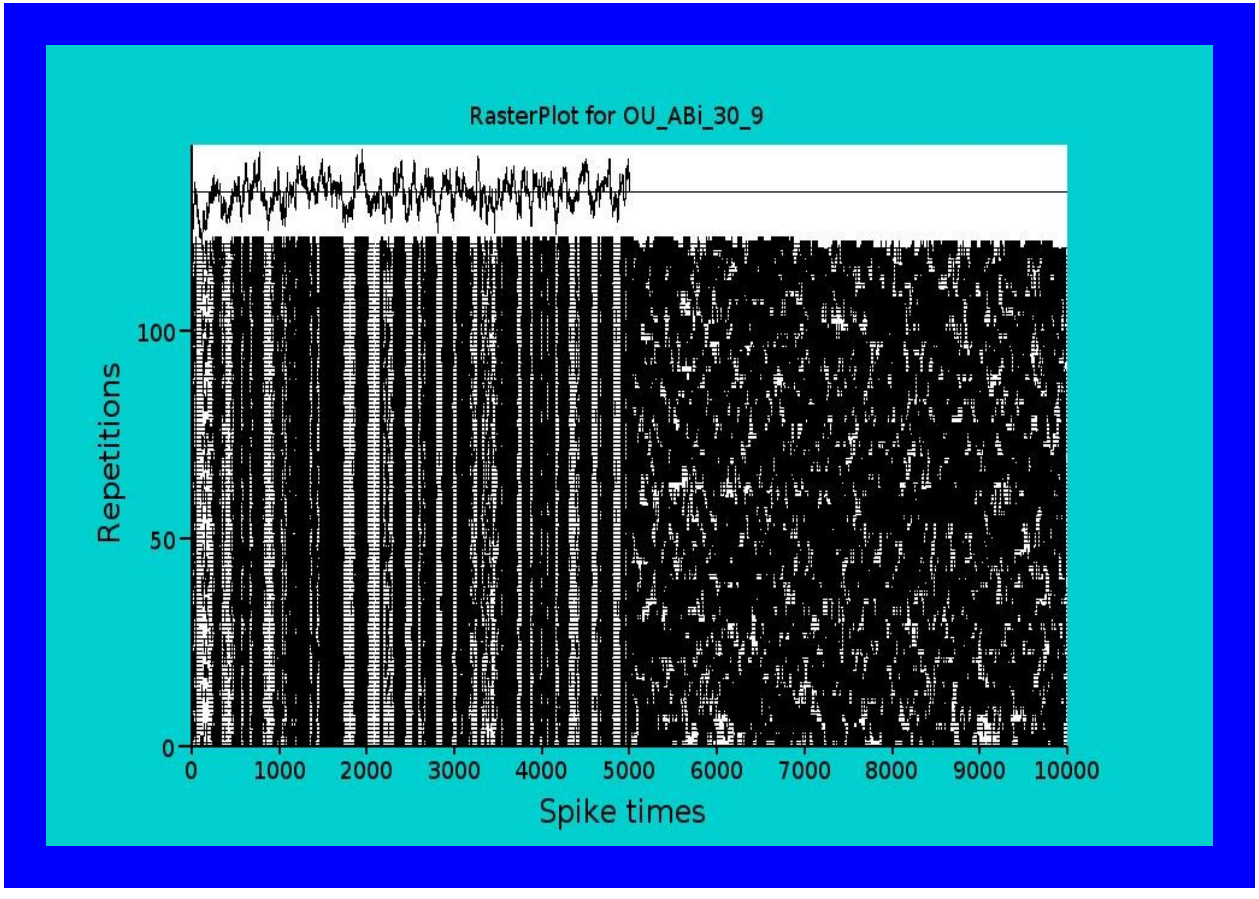


Spikes from H1

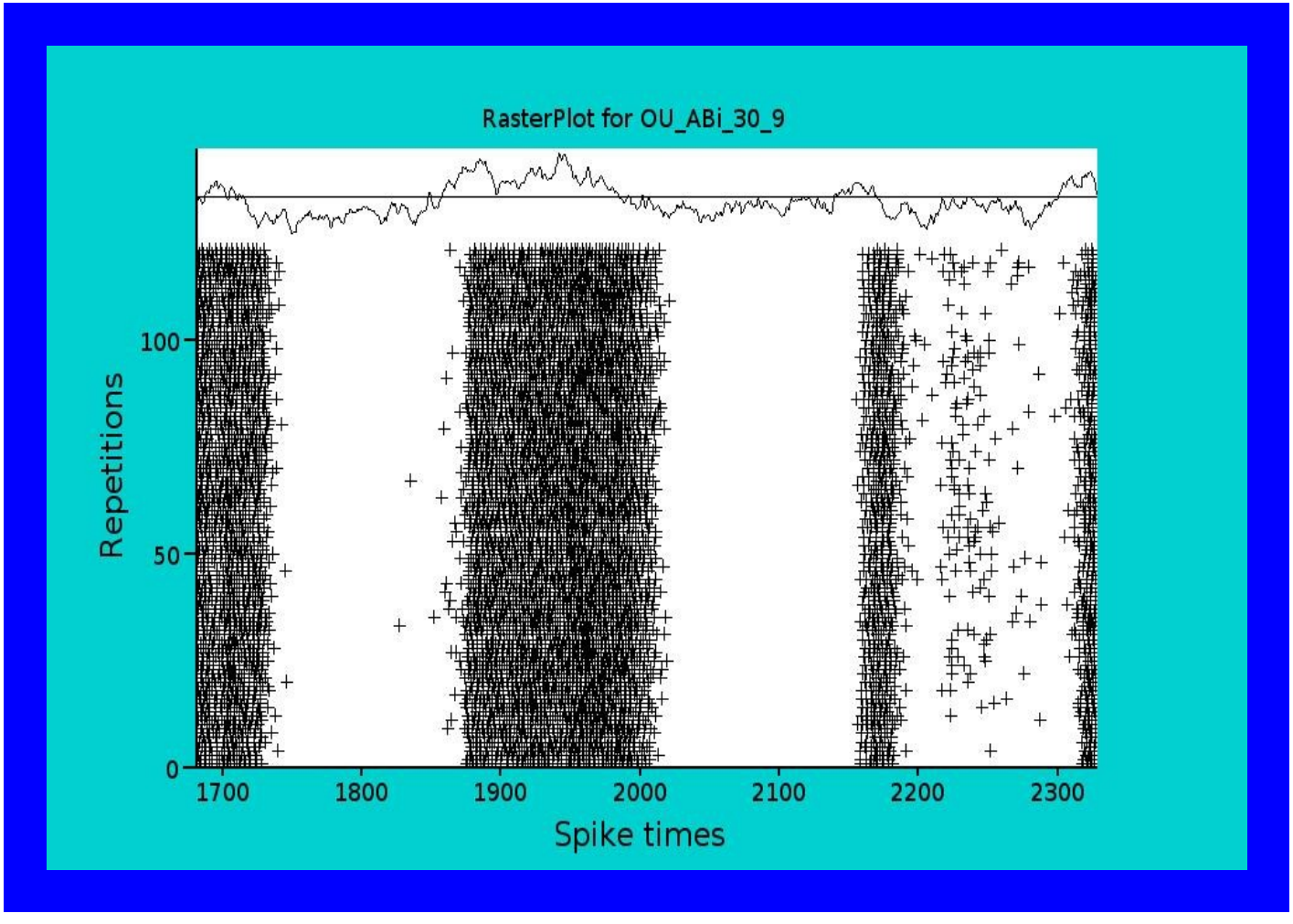


Raster plot for a typical experiment

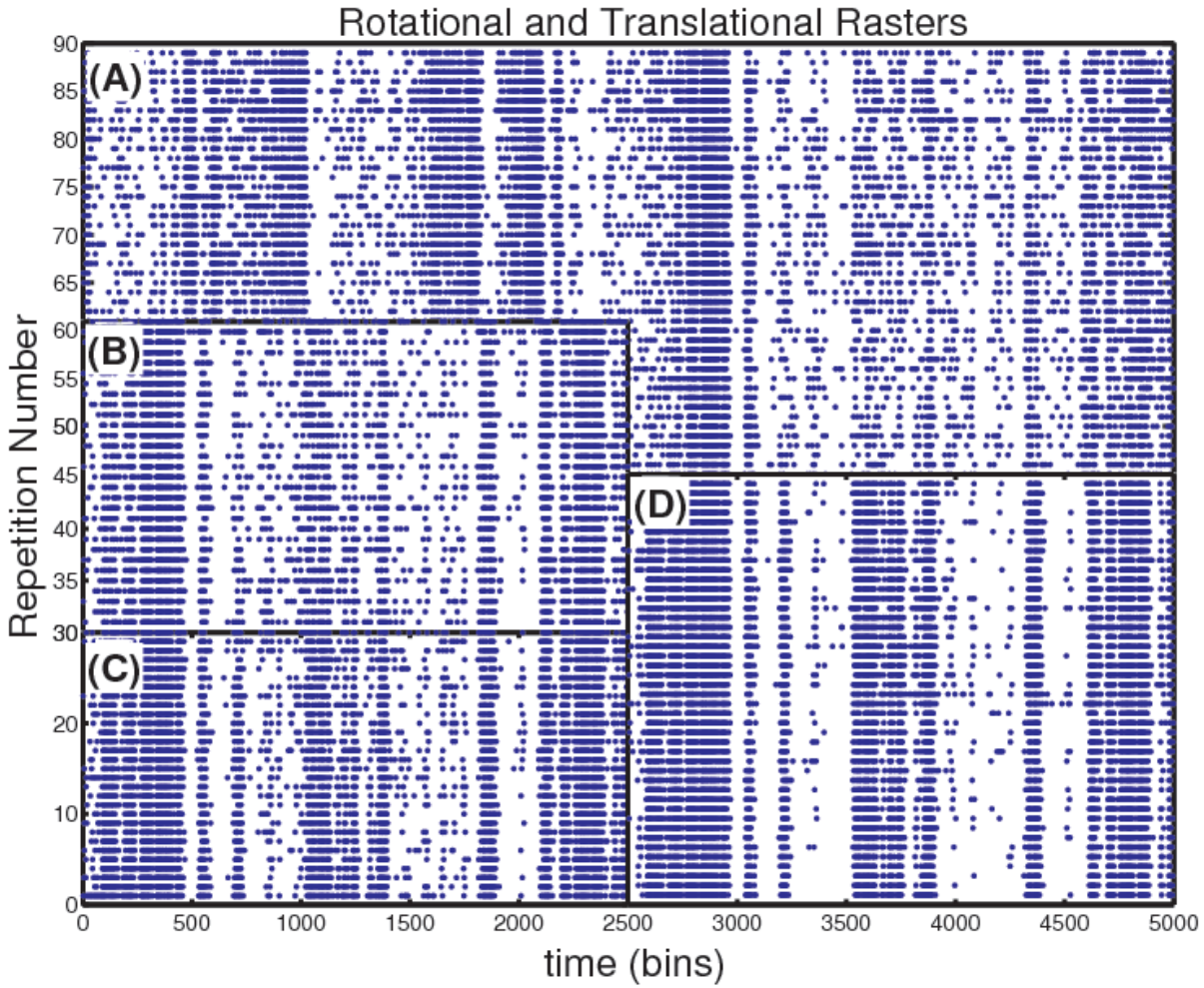
Show repeatedly the same stimulus for $t = 1 : 5000$ and different stimuli from $t = 5001 : 10000$.
Plot the occurrence of a spike as a dot, aligning the repetitions one on the top of the next...



Show spiking-onset and delay after zero-crossings = edges/discontinuities



Raster from left and right H1 with contralateral *simulation*



Reconstructing the stimulus from spike trains

Suppose we want to reconstruct the stimulus from the response of a single H1 neuron. We represent this response as a spike train

$$\rho(t) = \sum_{i=1}^{N_s} \delta(t - t_i),$$

which is a sum of delta functions at the spike times t_i. N_s is the total number of spikes generated by the neuron during the experiment.

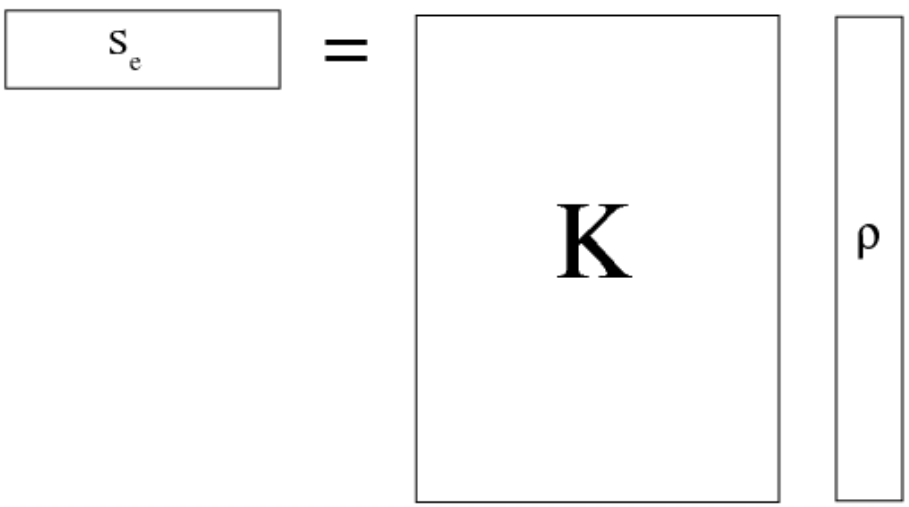
The simplest reconstruction extracts the stimulus estimate via a linear transformation

$$s_e(t) = \int_{-\infty}^{\infty} k_1(\tau)\rho(t - \tau)d\tau \qquad (1)$$

- with the kernel $k_1(t)$ to be determined.

In practice on the computer

Everything is discrete $\rightarrow$ bin the time. Select a reconstruction size of e.g. $n = 64$ bins and chop $\rho(t)$ into vectors of length n. $K_{i,j}$ will be a matrix of size $n \cdot n$ and $S_e(t)$ a row of length n.



Complete Volterra Series

The complete series would be like:

$$s_e(t) = \int_{-\infty}^{\infty} k_1(\tau)\rho(t-\tau)d\tau + \tag{2}$$

$$\int_{-\infty}^{\infty} k_2(\tau_1,\tau_2)\rho(t-\tau_1)\rho(t-\tau_2)d\tau_1 d\tau_2 + \ldots \tag{3}$$

- with the kernels $k_1(t), k_2(t)$ to be determined.

There is no convergence proof for this expansion, but heuristically we may say that it should be a valid approximation, if the average number of spikes per correlation time τ_c is small.

Determining the kernels

The kernels are determined, minimizing the χ^2:

$$\chi^{(2)}(k_1, k_2) = \langle \int dt[s(t) - s_e(t)]^2 \rangle. \tag{4}$$

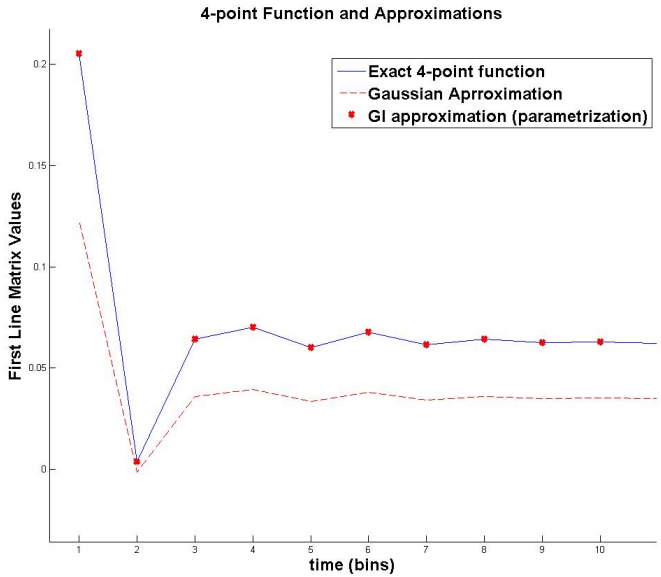
The brackets stand for an ensemble average with respect to the distribution of all possible stimuli. In a long experiment we average over $N_w \sim 10^5$ time windows of size T_w. Typically $T_w \sim 100$ milliseconds.

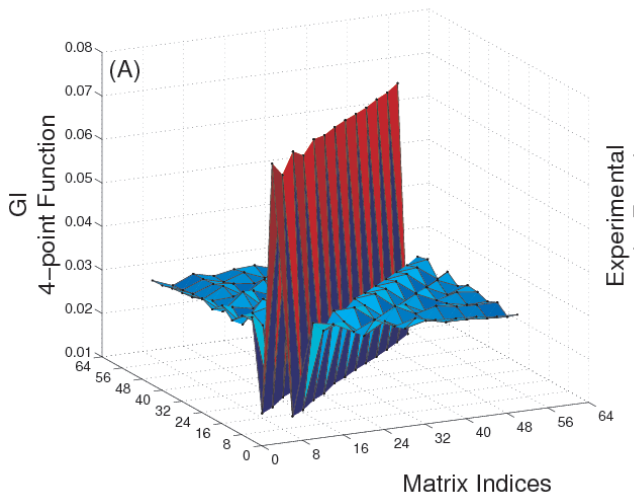
Since the functional equ.(4) is quadratic, the equations minimizing $\chi^{(2)}(k_1, k_2)$ are linear.
They involve correlation functions like:

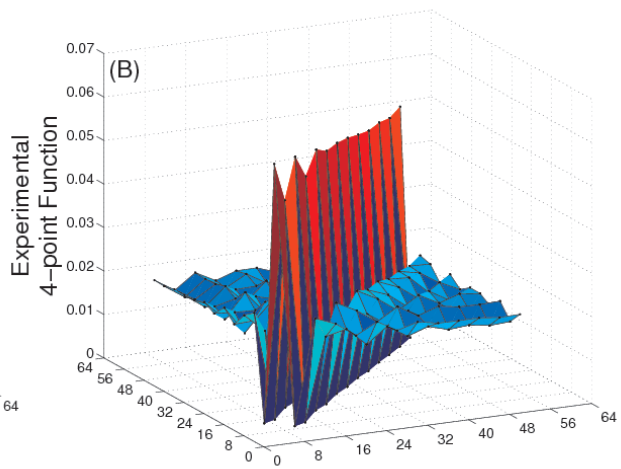
$$\langle s(t)\rho(t')\rangle, \langle \rho(t)\rho(t')\rangle,$$
$$\langle s(t)\rho(t_1)\rho(t_2)\rangle,$$
$$\langle \rho(t_1)\rho(t_2)\rho(t_3)\rho(t_4)\rangle$$
etc.

For a window of size $T_w = 128$, the matrices are of size $\sim (128^2 \cdot 2^2) \times (128^2 \cdot 2^2) \sim 10^{10}$!
Enter a gaussian-like approximation:

$$R^{(4)}(1,2,3,4) =$$
$$\mathbf{A}[R(1,2)R(3,4) + R(1,3)R(2,4) + R(1,4)R(2,3))] - \mathbf{B}$$


4-point Function and Approximations
Exact 4-point function
Gaussian Aprroximation
GI approximation (parametrization)
First Line Matrix Values
time (bins)


(A)
GI
4−point Function
Matrix Indices


(B)
Experimental
4−point Function

Is this useful?

1. The constants A and B are found to be independent of window-size T_w.
2. The 2-point function $R(t_1, t_2)$ is real, positive and symmetric in t_1, t_2, $\rightarrow$ complete set of eigenfunctions $\sim f_\mu(t)$:
   Expand everything in terms of $f_\mu(t)$:

$$\int dt_1 dt_2 f_\mu(t_1) R(t_1, t_2) f_\nu(t_2) = \delta_{\mu\nu}. \tag{5}$$

   Avoid large matrix inversions.

3. $$\mathcal{R}_{\mu\nu\alpha\beta} = A(\delta_{\mu\nu}\delta_{\alpha\beta} + 2\delta_{\mu\alpha}\delta_{\nu\beta}) - 2B\, n_\alpha n_\beta n_\mu n_\nu, \tag{6}$$

   where $n_\mu = \int dt f_\mu(t) \langle \rho(t) \rangle$.
4. Set up a $k_{12} \star \rho_1 \star \rho_2 \sim 1\%$-effect perturbation theory.

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$$\int dt_1 dt_2 f_\mu(t_1) R(t_1, t_2) f_\nu(t_2) = \delta_{\mu\nu}. \tag{5}$$

   Avoid large matrix inversions.

3. $$\mathcal{R}_{\mu\nu\alpha\beta} = A(\delta_{\mu\nu}\delta_{\alpha\beta} + 2\delta_{\mu\alpha}\delta_{\nu\beta}) - 2B\, n_\alpha n_\beta n_\mu n_\nu, \tag{6}$$

   where $n_\mu = \int dt f_\mu(t) \langle \rho(t) \rangle$.

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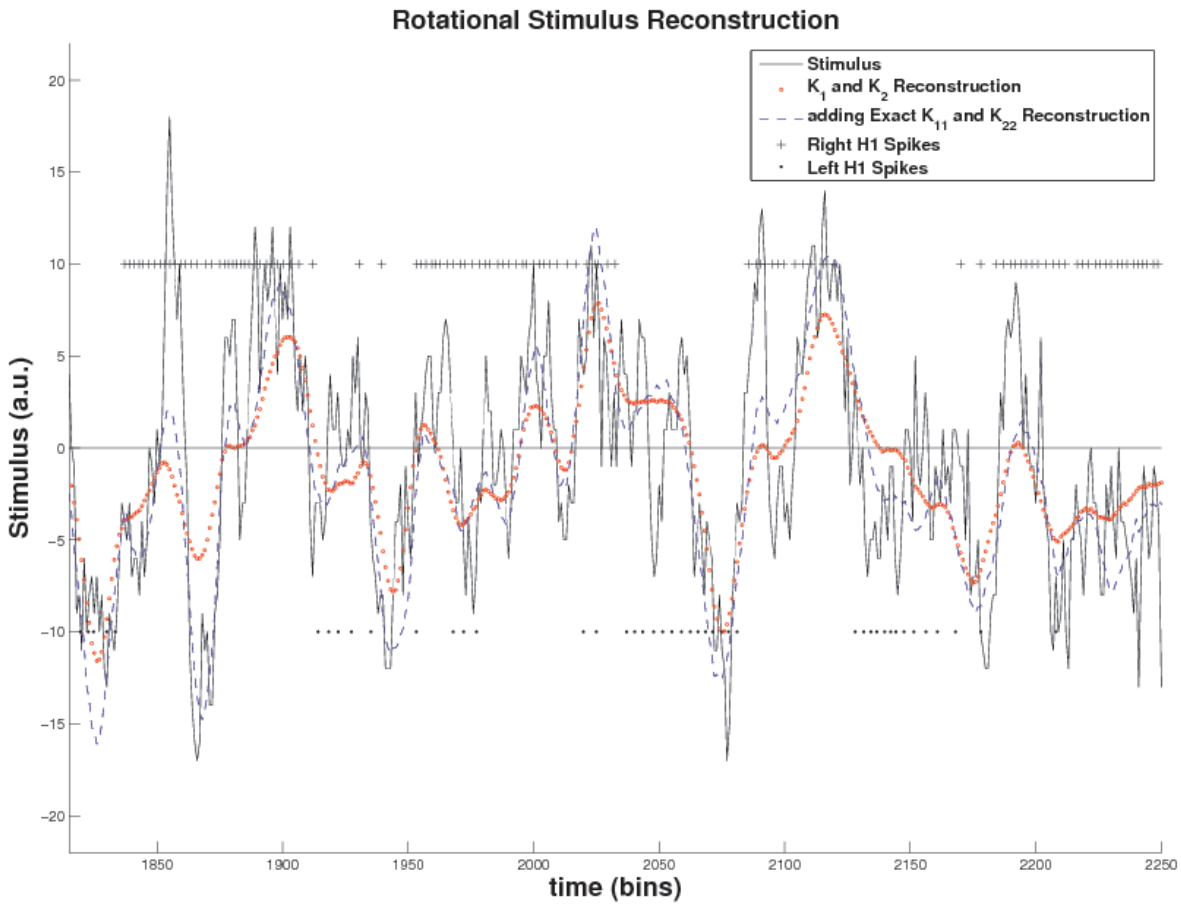
Stimulus Reconstruction via Volterra Series

- viewed thru a Gaussian kernel



What are the shortcomings?

- Encode: $S(t) \rightarrow \rho(t)$
  Dimensional Reduction $\rightarrow$ Relevant features ?

Decode: $\rho(t) \rightarrow S(t)$
Reconstruction in real time
Updating correlation functions !!!!!!

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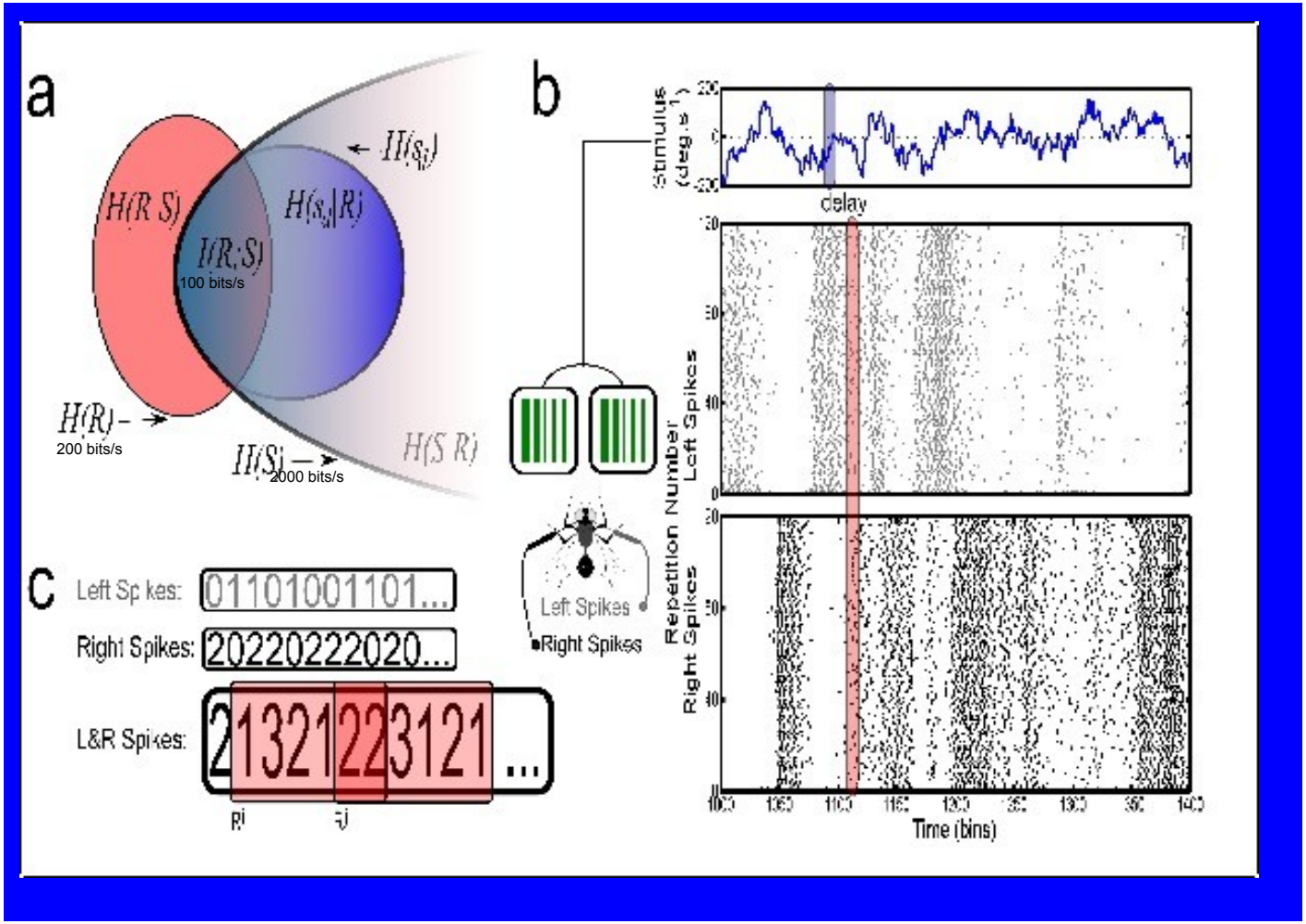
Entropy Reduction and Coding Efficiency



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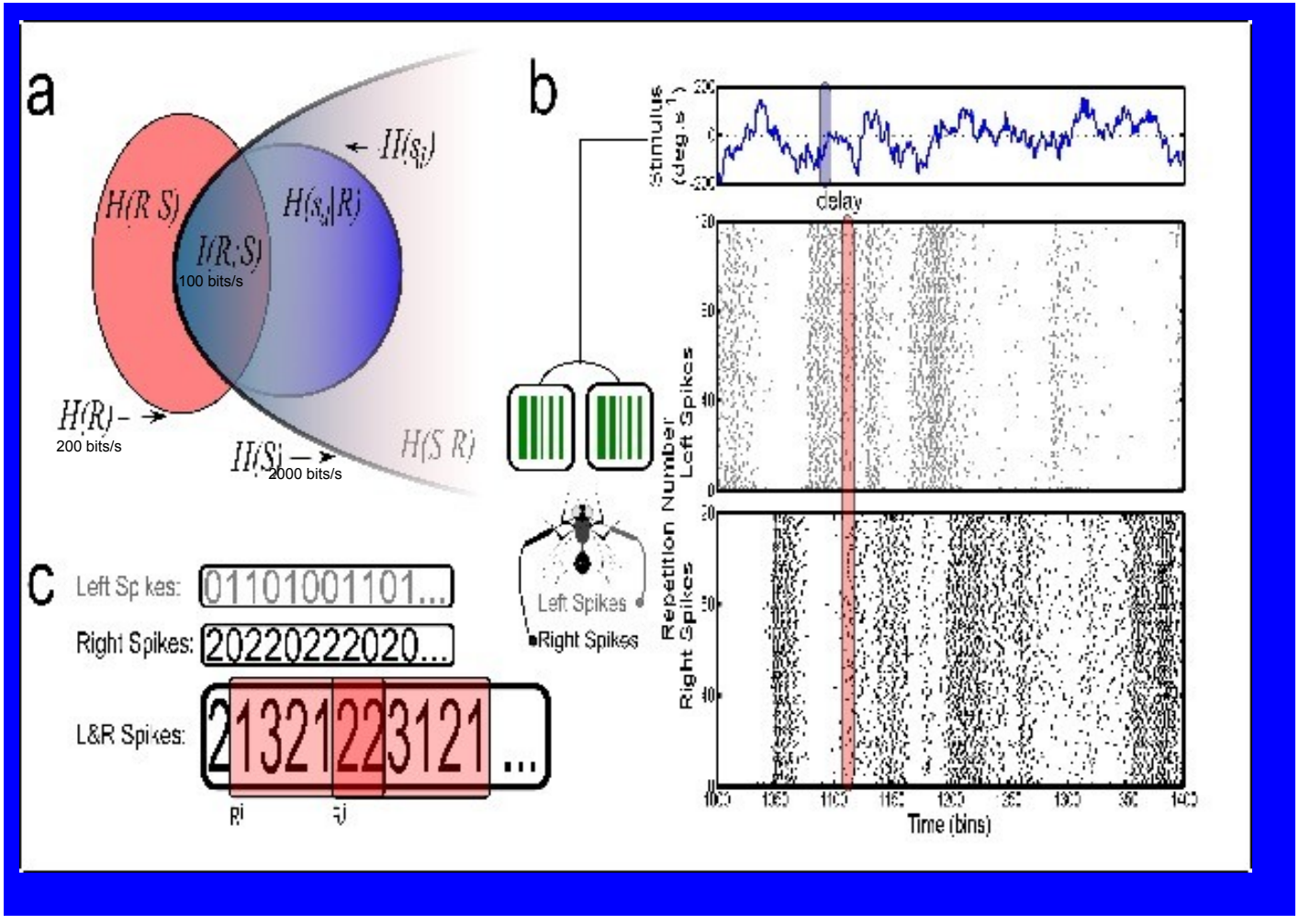

- Stimulus-Entropy-Rate ~ 1500 bits/sec
  Spike-Entropy-Rate ~ 100 bits/sec

Guess what is important

- **Do we want to turn left or right ?**
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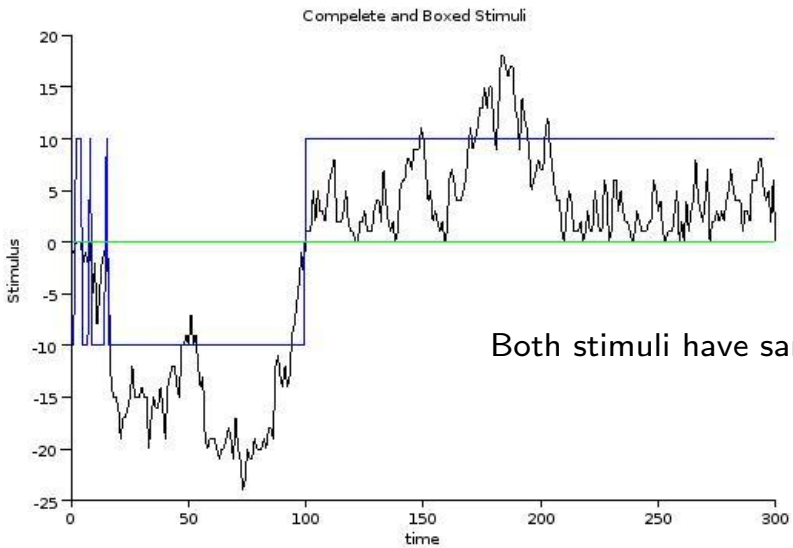
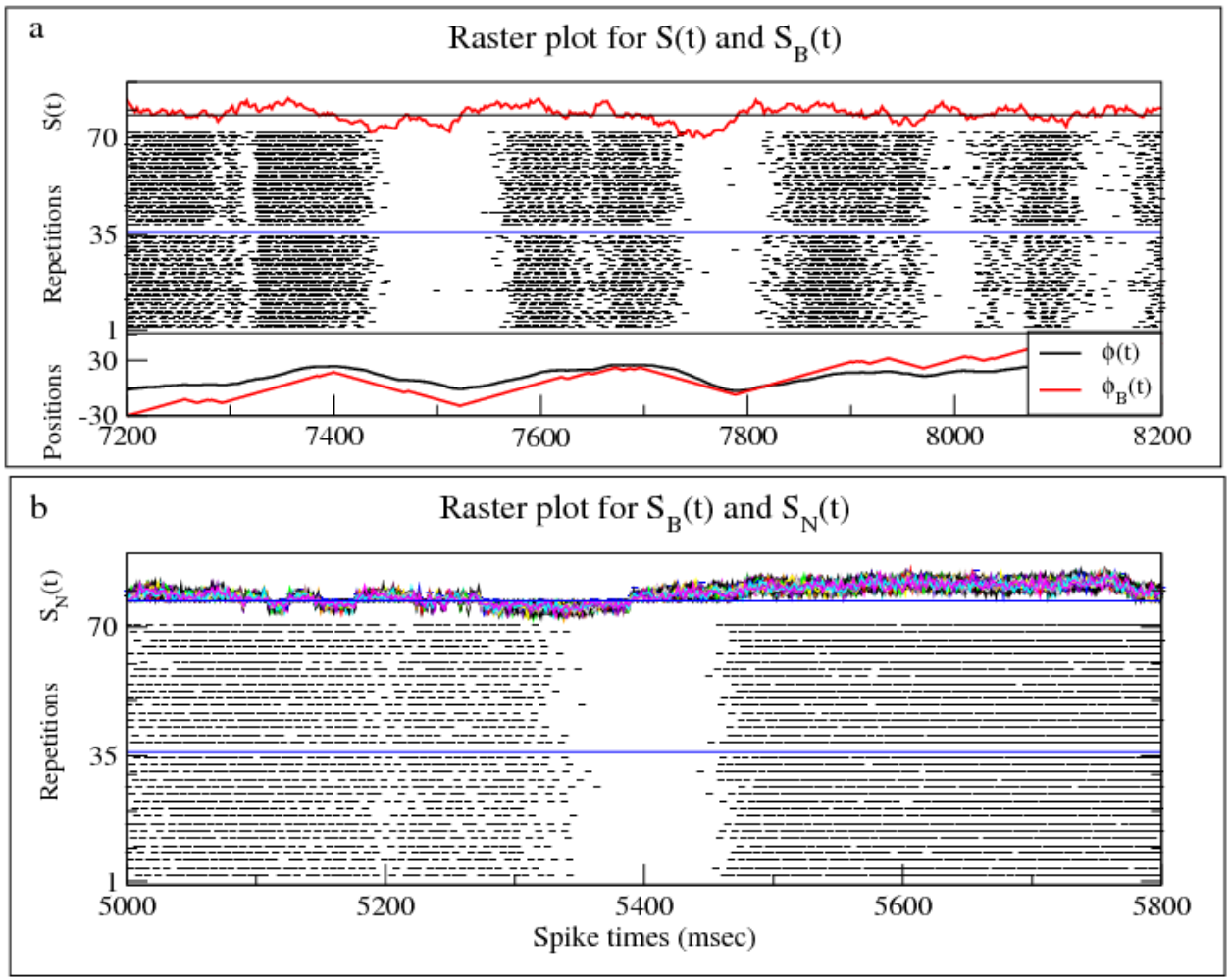


Both stimuli have same variance !

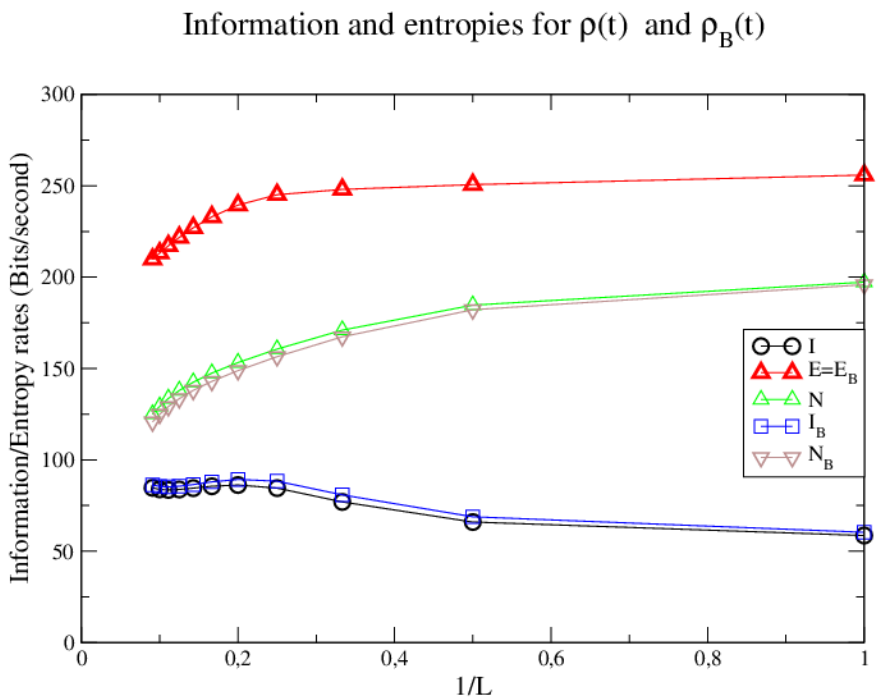
We expect utterly different H1 responses for the complete and the boxed stimulus!! Remember the nice reconstructions!

Boxed and Complete Stimulus Rasters



Same Mutual (Shannon) Information and Entropies

Global quantities - time ordering is lost



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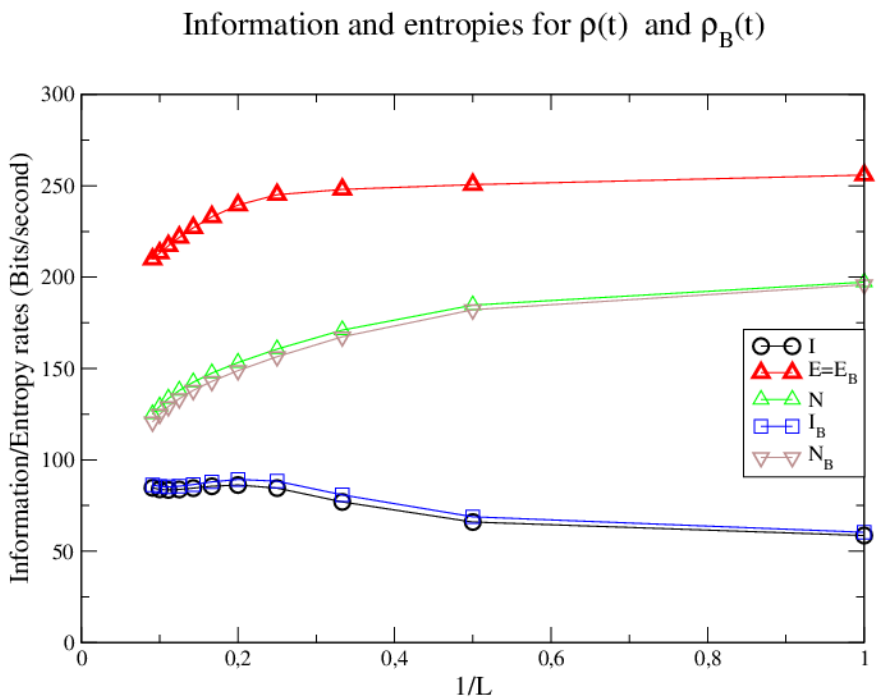

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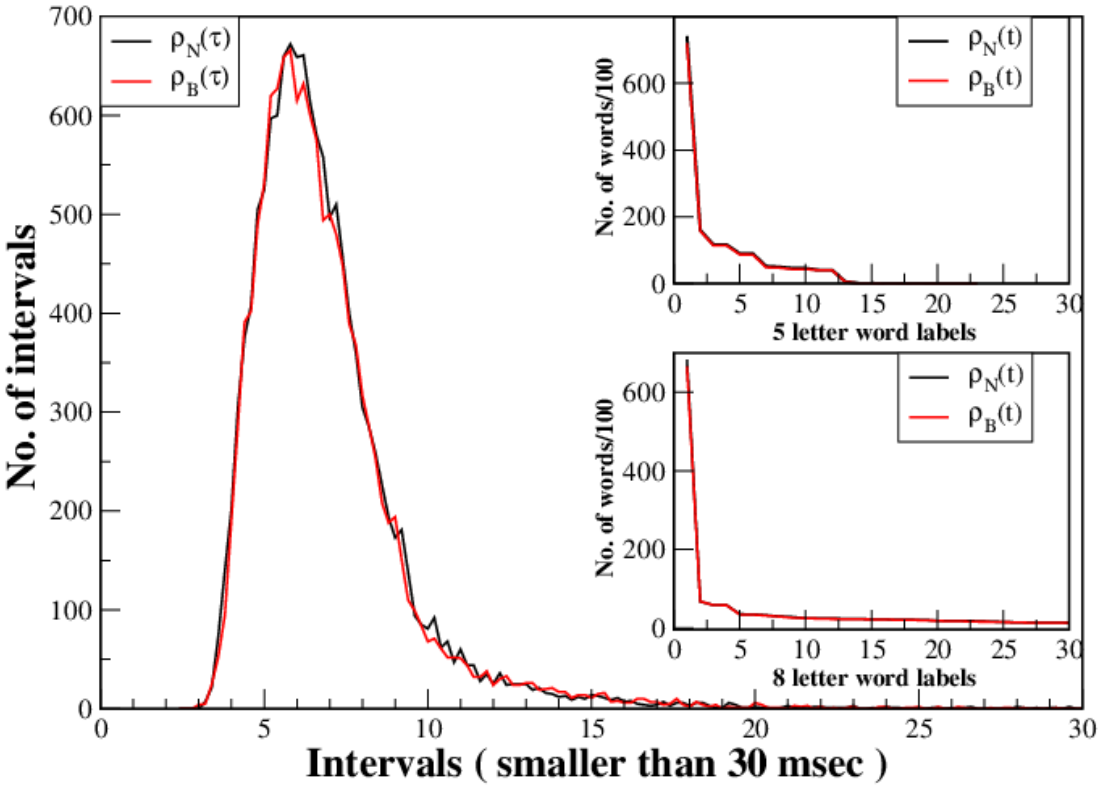
Interval and Word Distributions of $\rho(t)$ and $\rho_{Boxed}(t)$

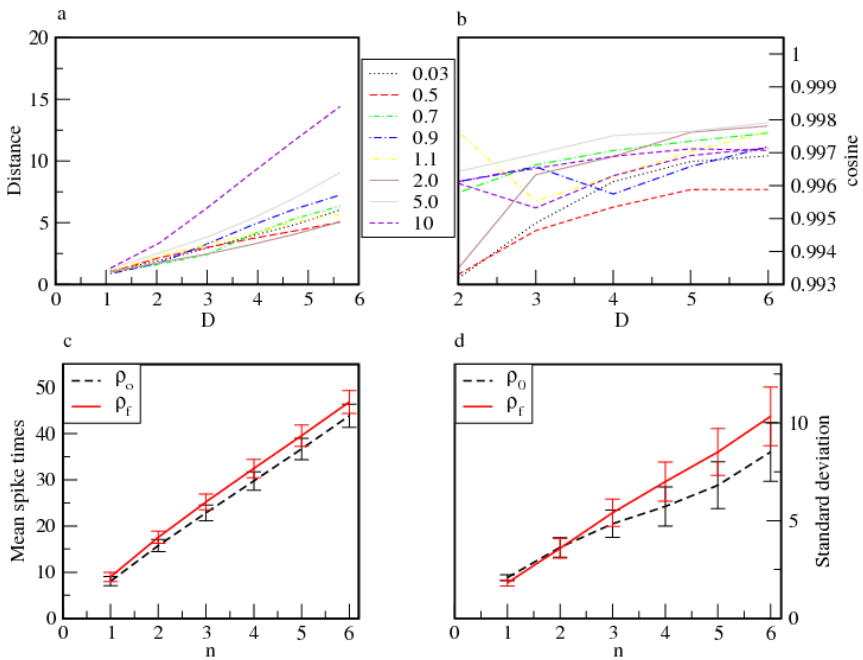


Embed spikes into a D-dimensional euclidean space

Different stimuli with same zero-crossing and same statistics (No boxed stuff - it is not *natural*!)

A spike-time sequence with D spikes is uniquely represented as a point $\vec{r}$ in a D-dimensional euclidean space: we don't loose the timing-structure!

a: Euclidean distances between $\vec{r_o}$ and $\vec{r}_f$: $\langle|\vec{r_o}-\vec{r_f}|\rangle$ vs. D. The averages $\langle.\rangle$ are over all ZC's.
b: Cosine between $\vec{r_o}$ and $\vec{r}_f$: $\langle\cos(\vec{r_o},\vec{r_f})\rangle$ vs. D. **c:** Mean of aligned spike-times after ZC's for ρ_o and ρ_f.



Mean distance/cosines for various stimuli

Mean/variance of spike-times

For complete elucidation of the neural code, we would need an order of magnitude more data.

Reconstructing Spiking Onset

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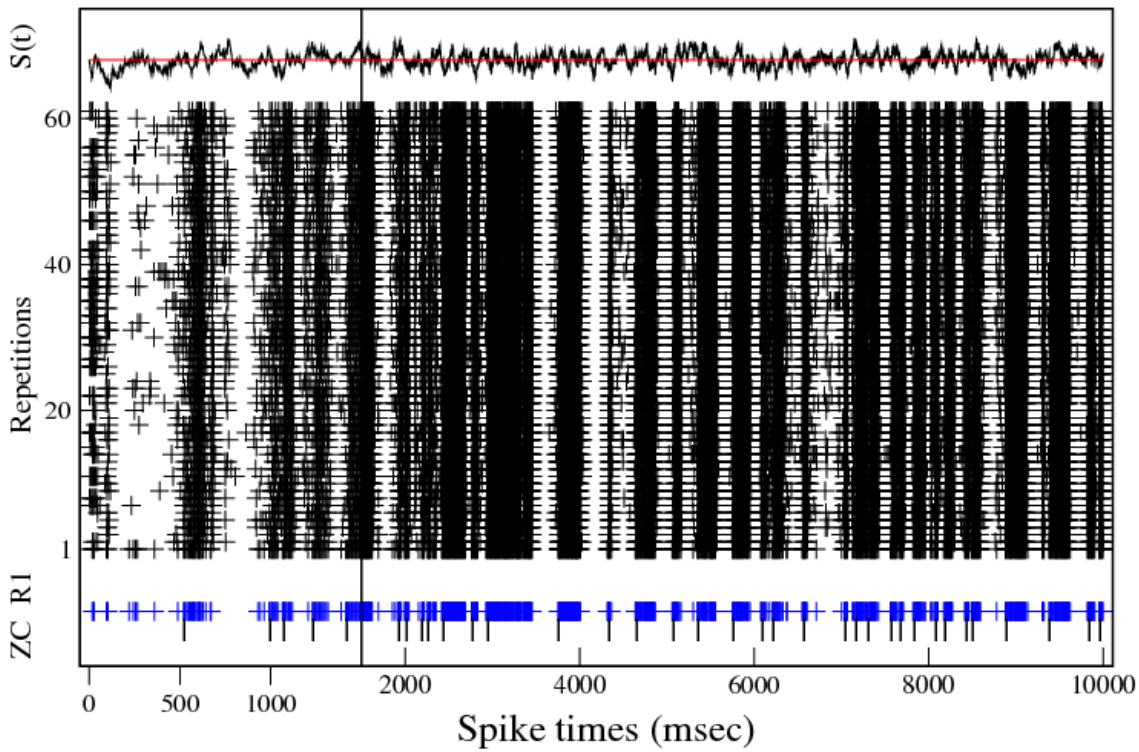
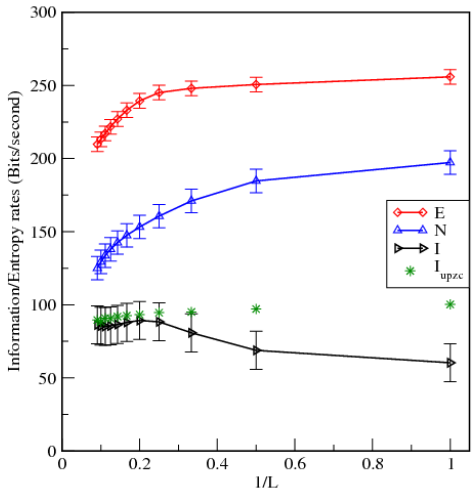
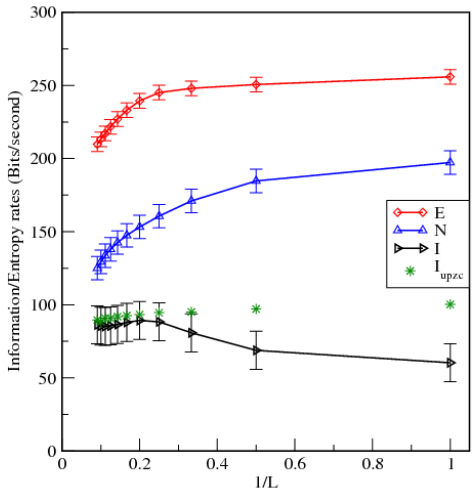




- Conclude that $I_1 \sim I_0$
- **The majority of the information which the system extracts from the scene is contained in the discontinuities!**
- CONCLUSION: Zero-crossings($*$) are of paramount importance, they are almost everything the fly encodes. The total mutual information is $\sim$ equal to information necessary to encode zero-crossings.



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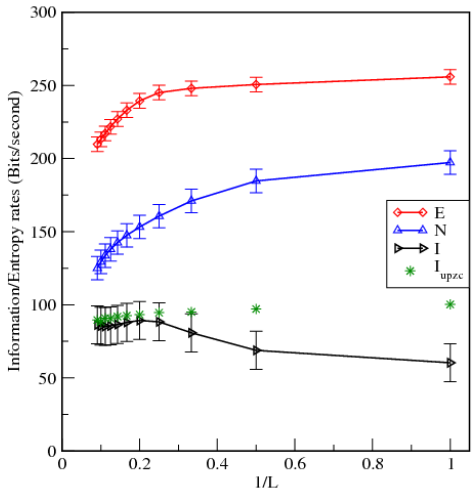

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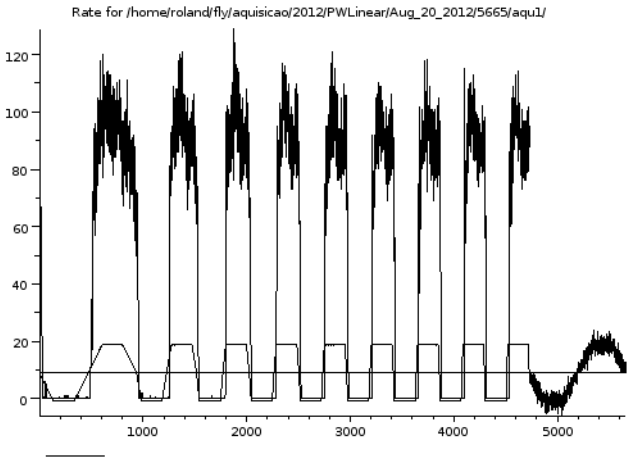
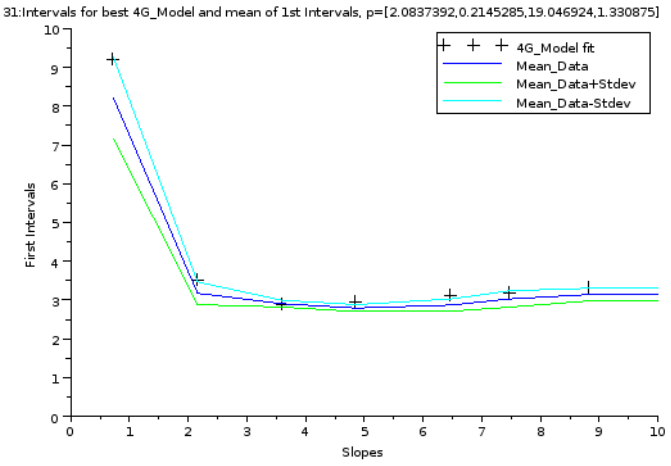
Rate and Slopes - *Intervals code for the piecewise linear stimulus*



Rate



First Intervals vs. Slope.

Knowing one interval, we can estimate the stimulus in

REAL TIME!

Conclusions red=true, green=hope !

1. It is possible to know the meaning of each spike/spike-sequence!
2. It is possible to decode the sequence in real time!
3. Fast sensory modules are simple and robust.
4. There are no fast, simple and robust *all-purpose* modules in the brain.
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THANKS