The Abdus Salam
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Winter School on Quantitative Systems Biology

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An engineer's view of early visual processing: De-noising and predictive coding n the retina and the LGN

M. Chklovskii
Howard Hughes Medical Inst.
Virginia
USA

Strada Costiera, 11 - 34151 - Trieste - Italy • Tel. +39 0402240111 • Fax. +39 040224163 • sci_info@ictp.it • www.ictp.it
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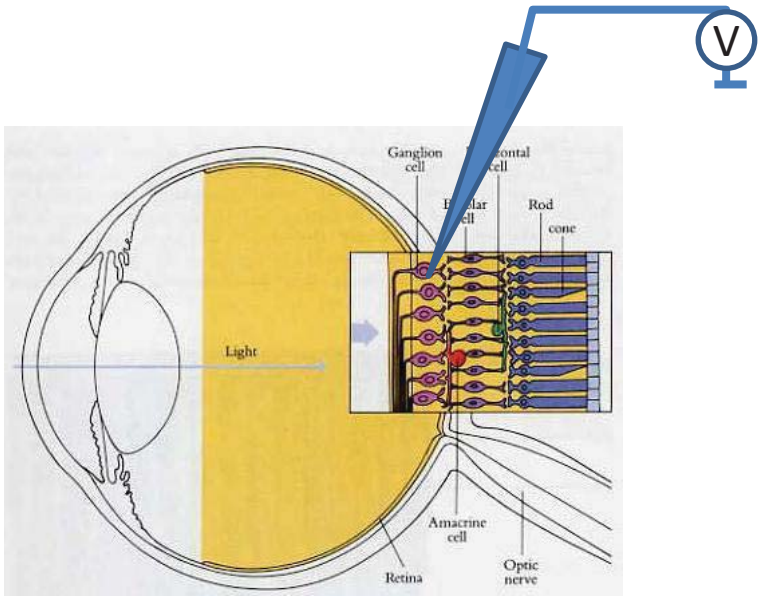
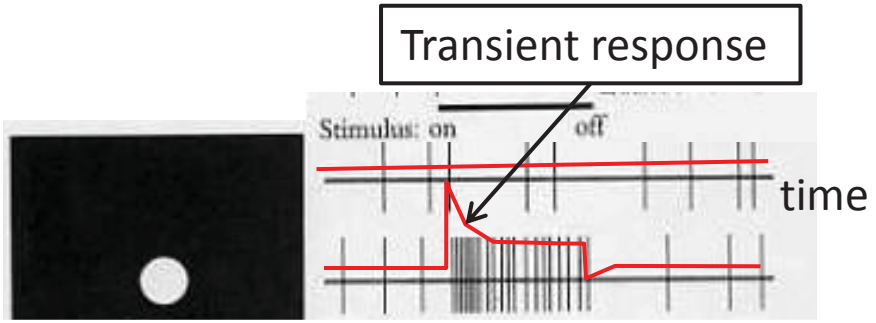
An engineer's view of early visual processing and neuronal spike generation

Dmitri "Mitya" Chklovskii

Janelia Farm, Howard Hughes Medical Institute

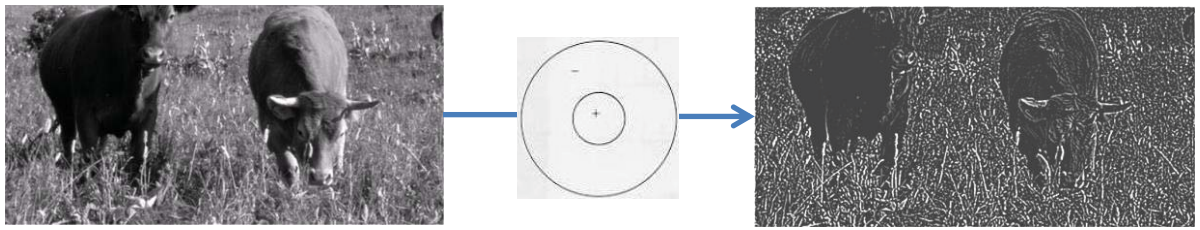
Response of a retinal ganglion cell to light





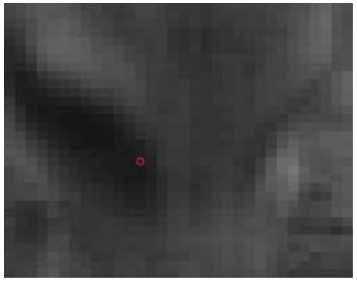
Kuffler (1960s)

Center-surround receptive field

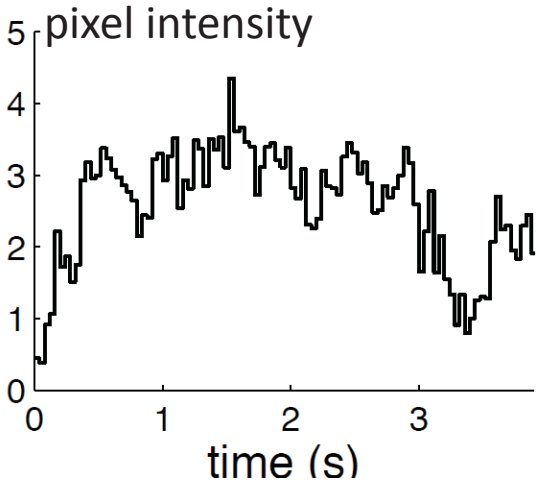


Why spatial and temporal edge detectors?

natural scene movie

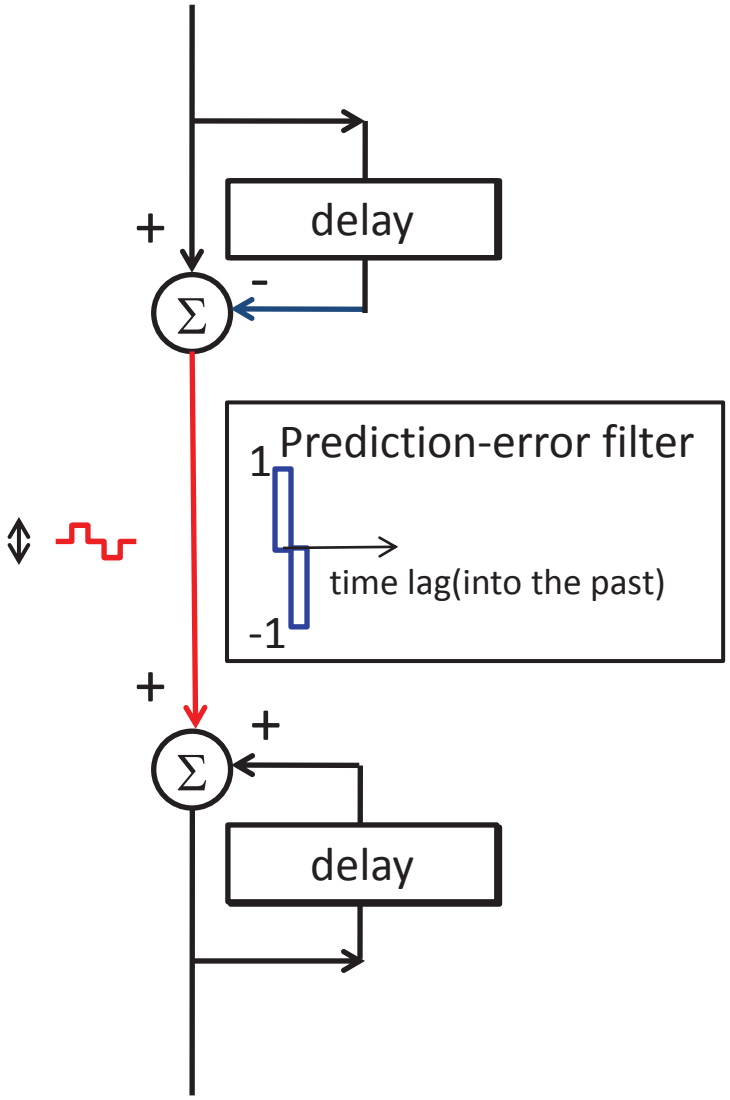


van Hateren

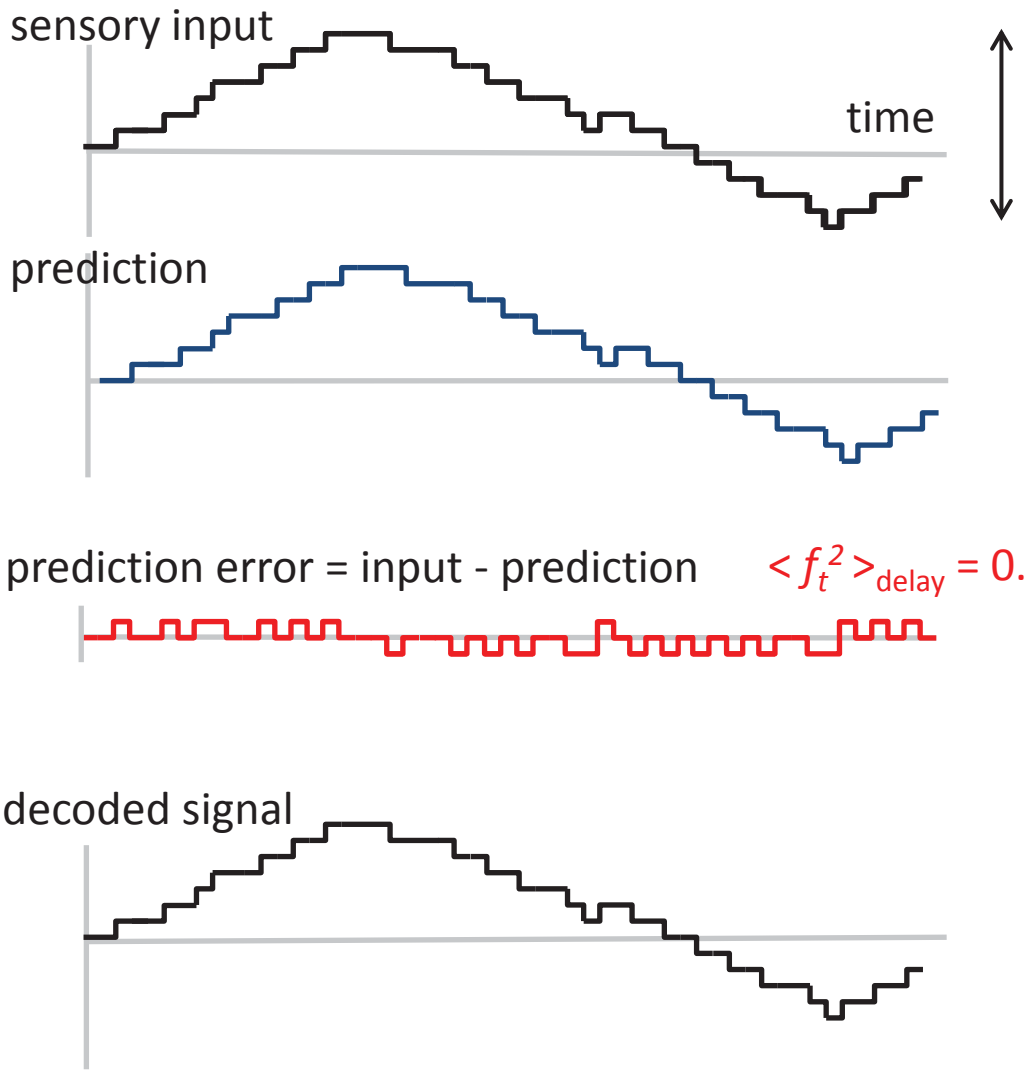


Attneave '54, Barlow '61

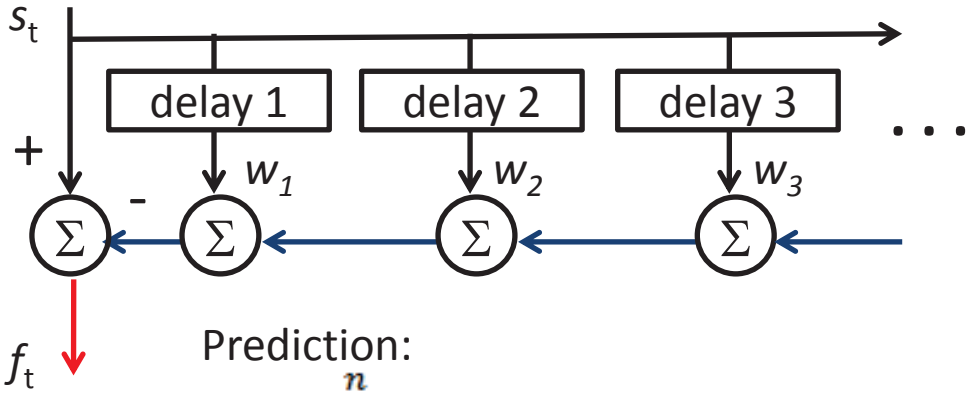
Predictive coding in signal processing



Discrete signal, discrete time example



Optimal linear prediction



Prediction:

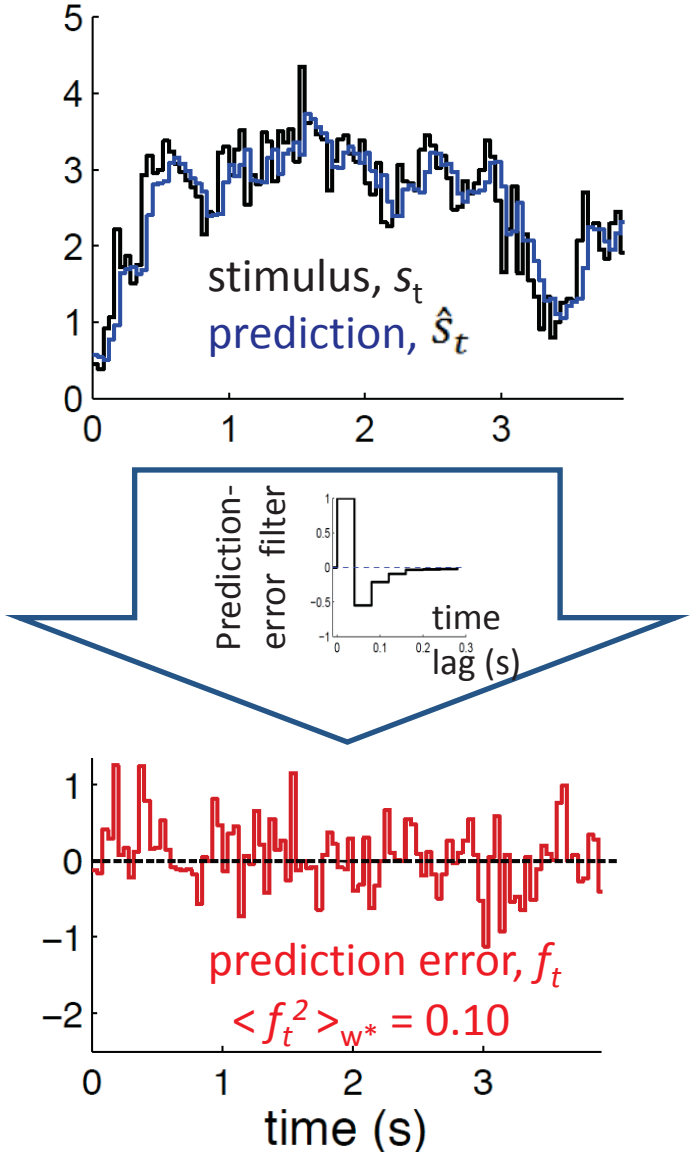
$$\hat{s}_t = \sum_{i=1}^{n} w_i \, s_{t-i}$$

Transmitted prediction error:

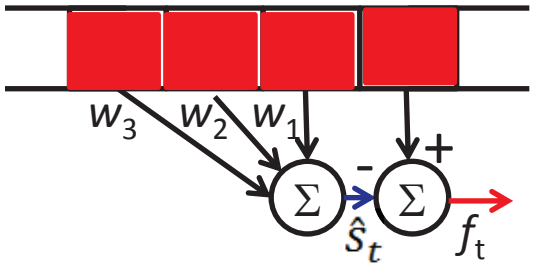
$$f_t = s_t - \hat{s}_t = s_t - \sum_{i=1}^{n} w_i s_{t-i}$$

Optimal prediction-error filter minimizes prediction error for a given stimulus ensemble:

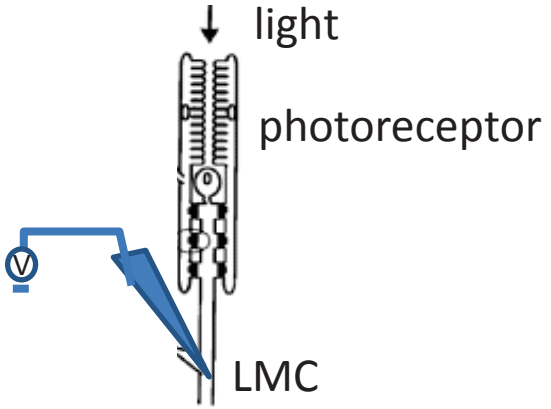
$$\boldsymbol{w}^* = \underset{\boldsymbol{w}}{\operatorname{argmin}} \langle f_t^{\,2} \rangle_t = \underset{\boldsymbol{w}}{\operatorname{argmin}} \left\langle \left[s_t - \sum_{i=1}^{n} w_i \, s_{t-i} \right]^2 \right\rangle_t$$



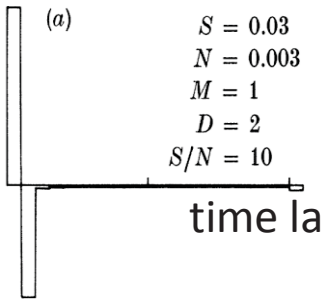
Comparison of predictive coding theory with experiment

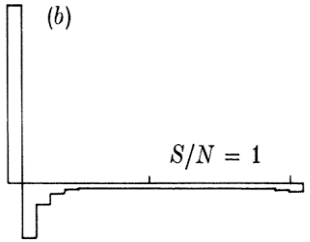


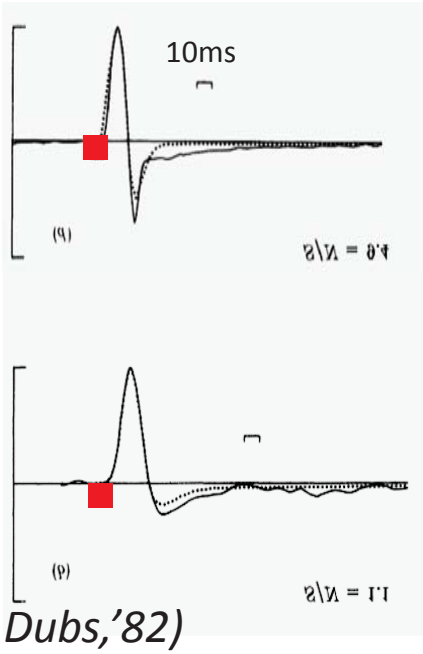
Optimal linear filter



Impulse response of fly LMC (L1 or L2), inverted

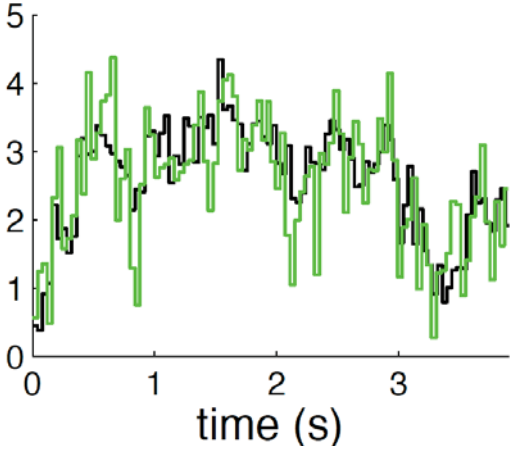


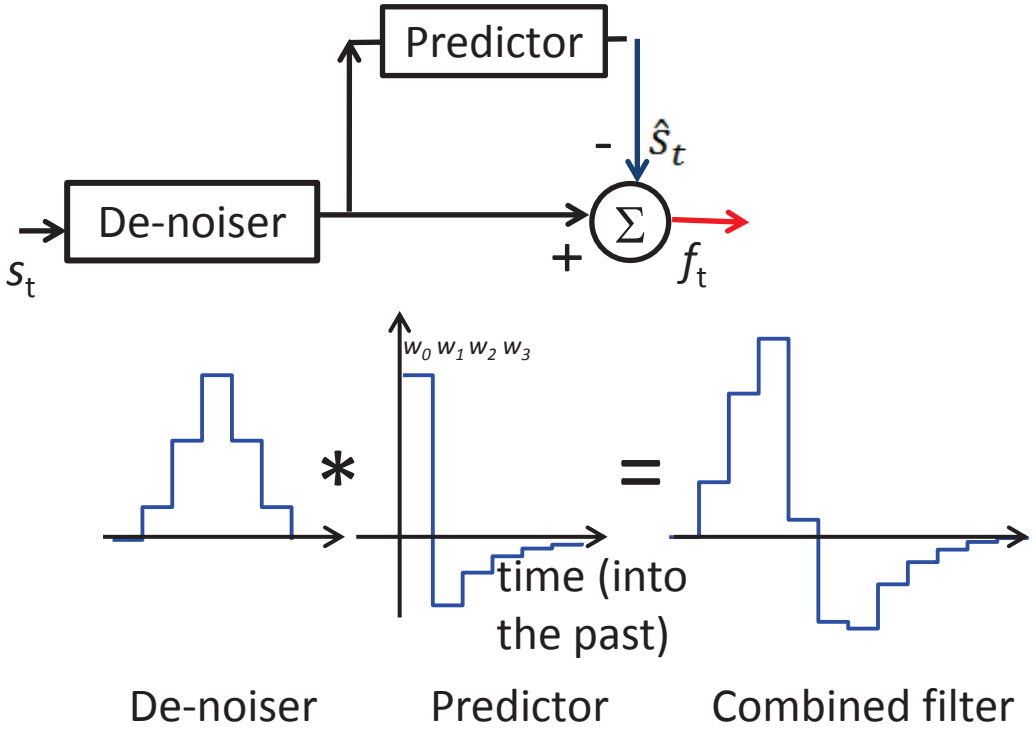


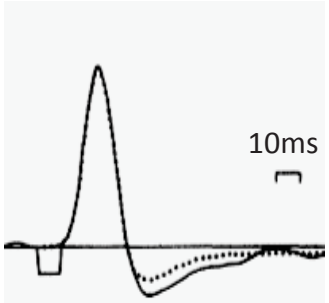


(Srinivasan, Laughlin & Dubs,'82)

Combination of optimal de-noising and prediction-error filters

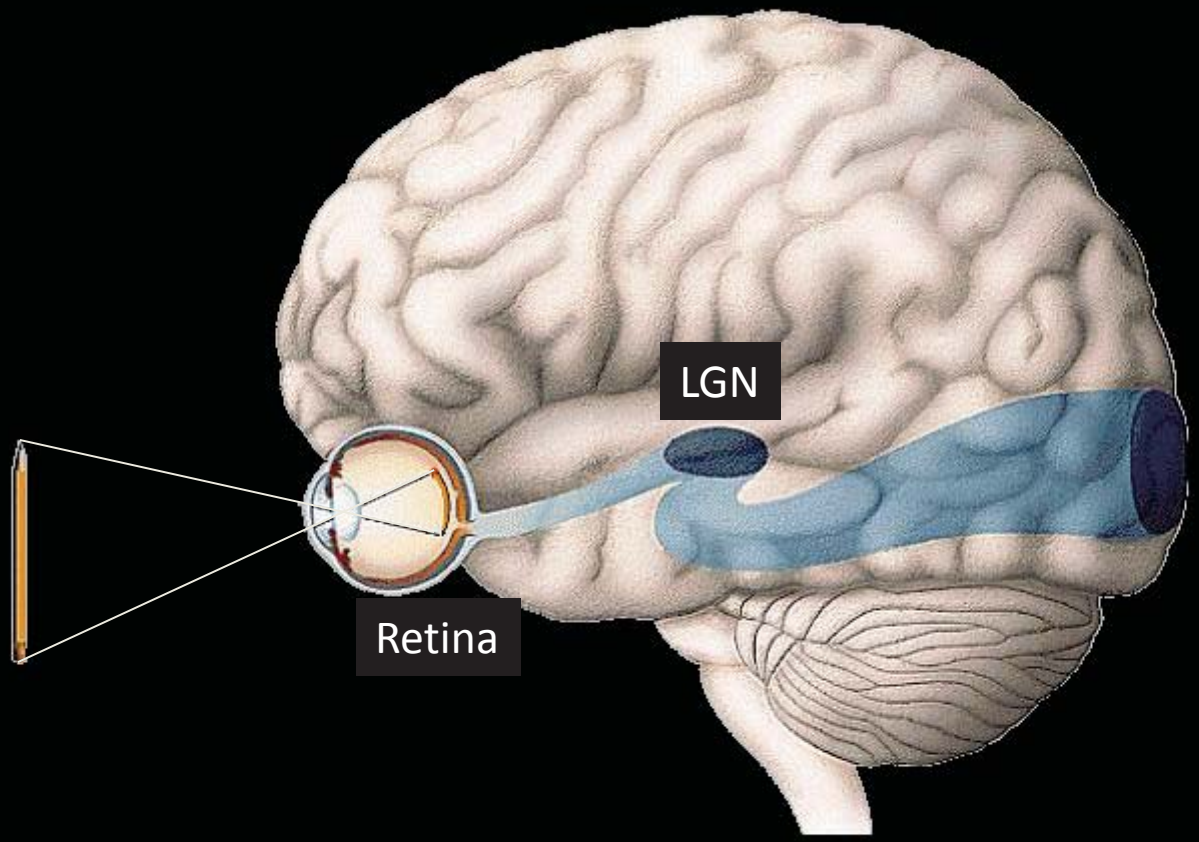




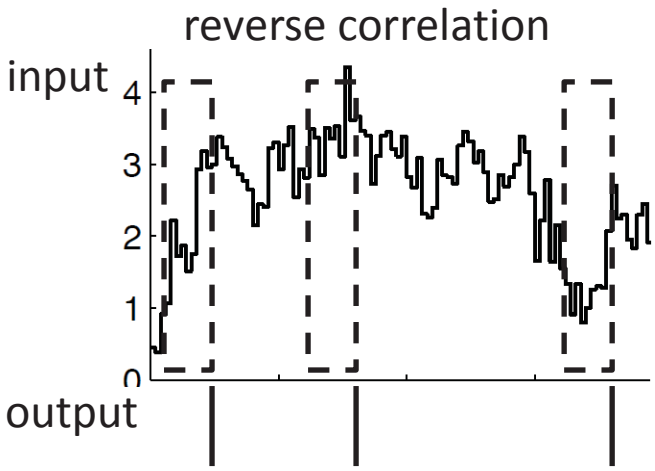


(Srinivasan, et al '82)

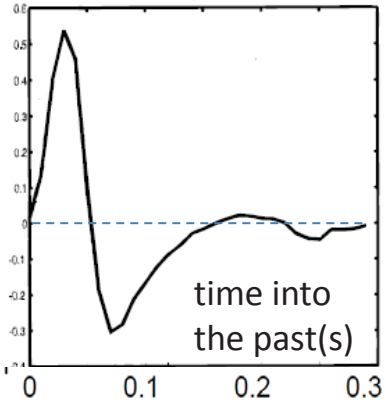
Human visual pathway



Measuring receptive fields using reverse correlation

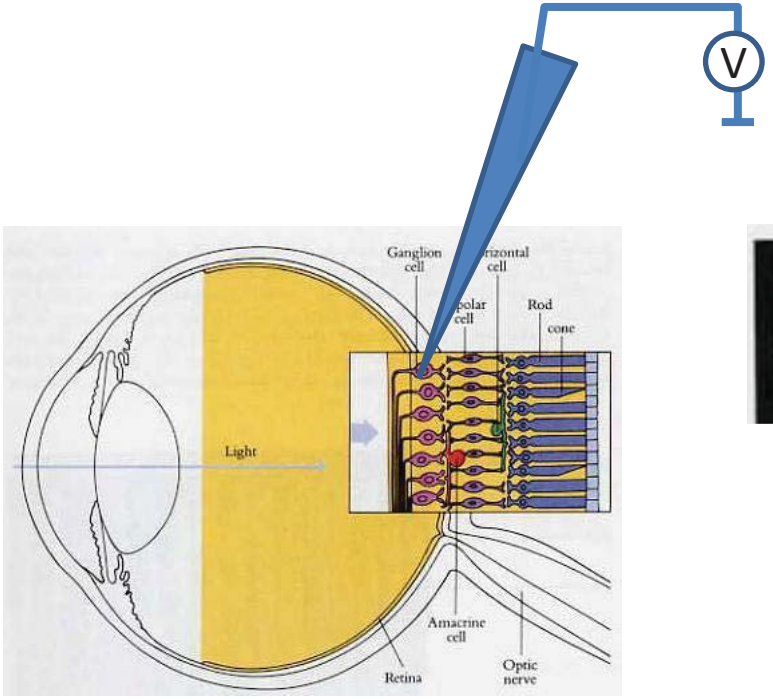


Temporal receptive field of cat LGN neuron



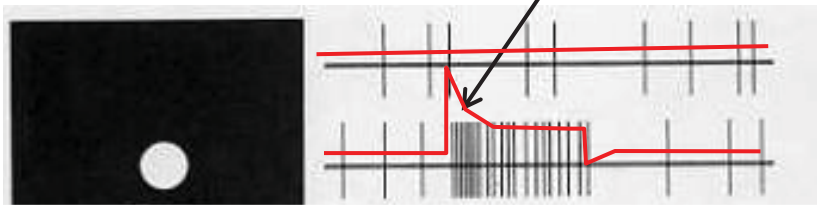
Wolfe & Palmer, 1998

Response of retinal ganglion cells to light

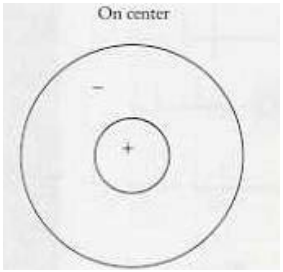


Kuffler (1960s)

Transient response

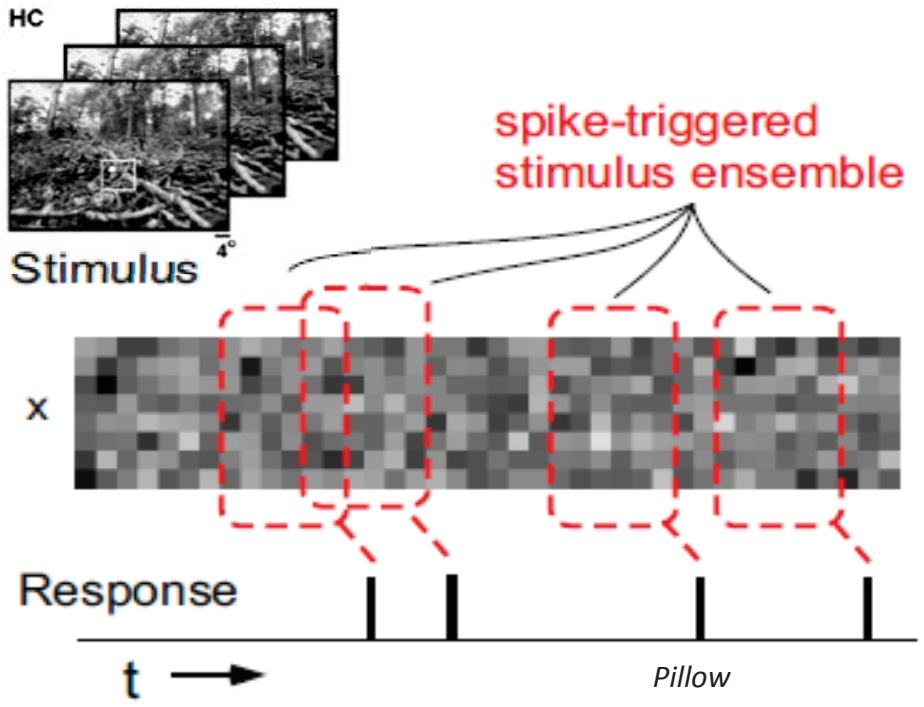


Center-surround receptive field

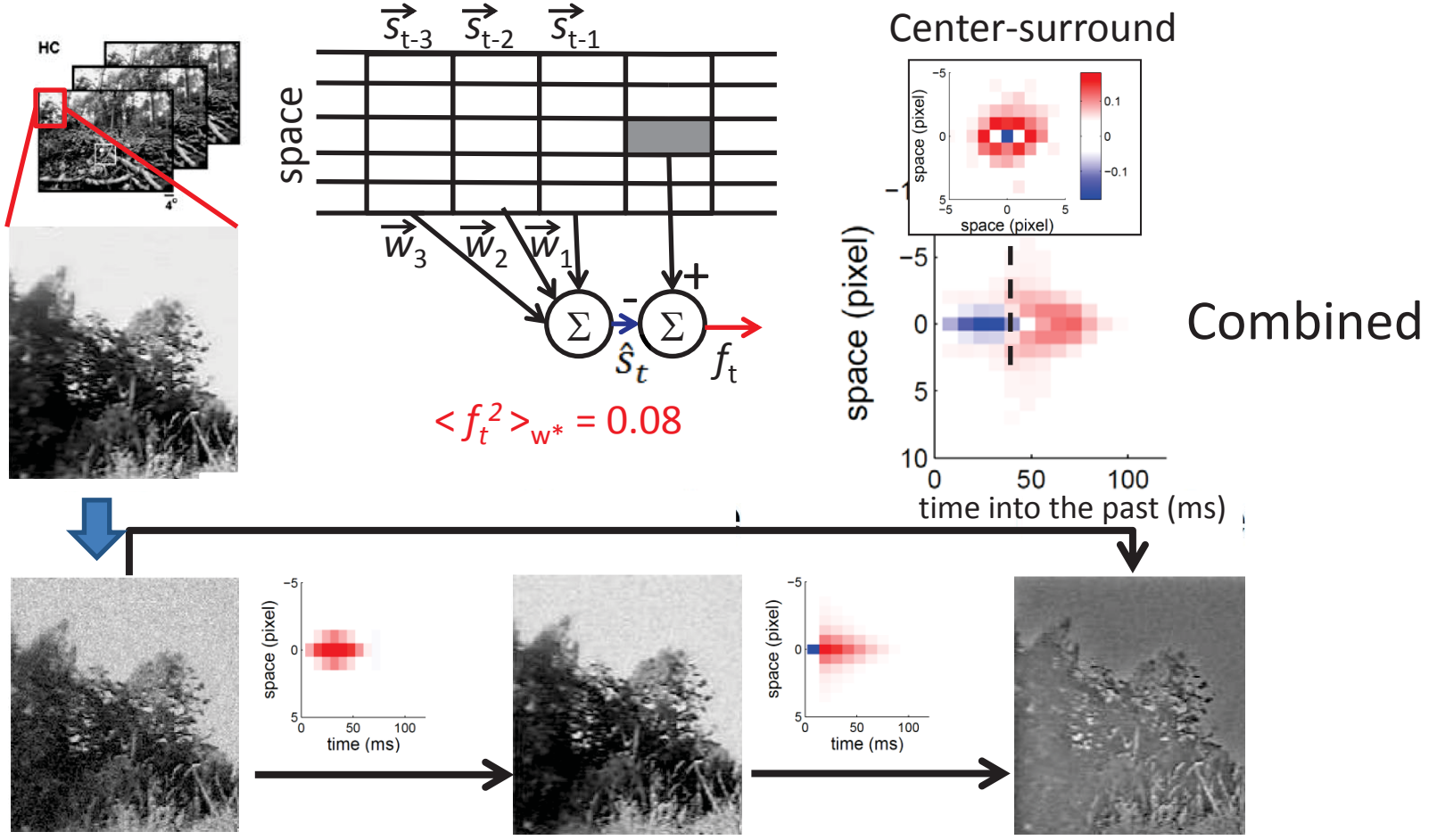


Srinivasan, Laughlin, & Dubs, 1982
Atick, 1991
Van Hateren, 1993
Rao & Ballard, 1999

Measuring spatio-temporal receptive field (STRF) using reverse correlation



Optimal spatio-temporal prediction-error filter

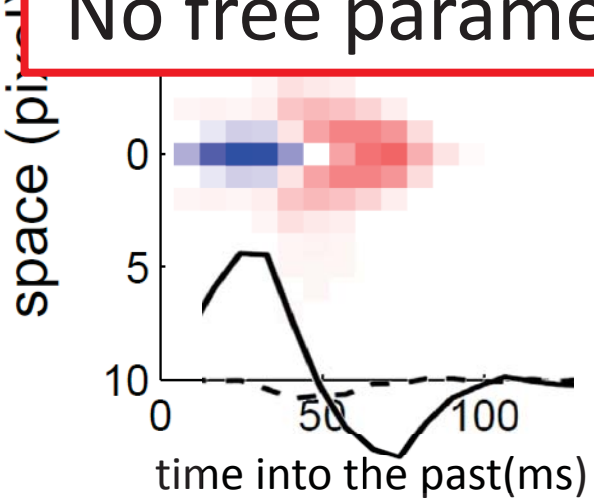


Ziqiang Wei
Tao Hu

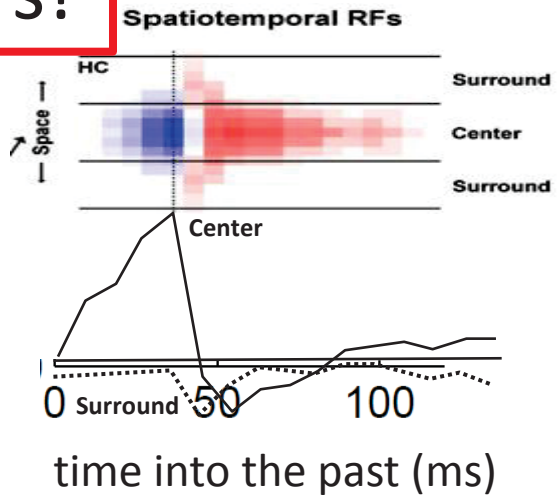
Optimal linear filter and spatio-temporal receptive field (STRF)

Optimal linear filter

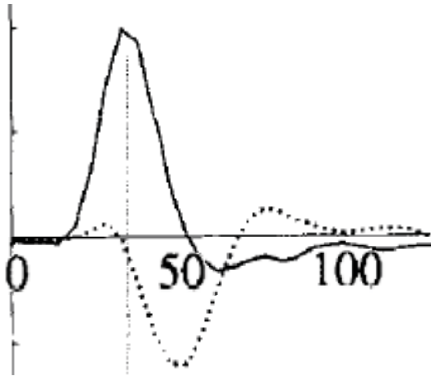
No free parameters!

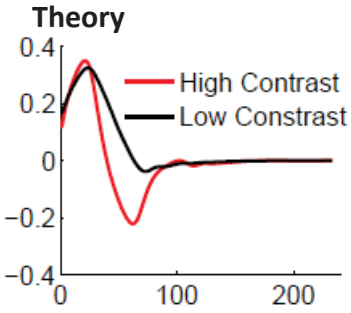


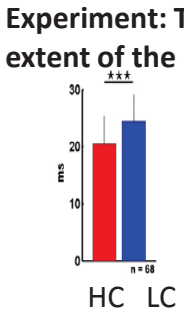
Cat LGN *(Lesica, et al., '07)*



Locust LMC (L1 or L2)
(James & Osorio, 96)

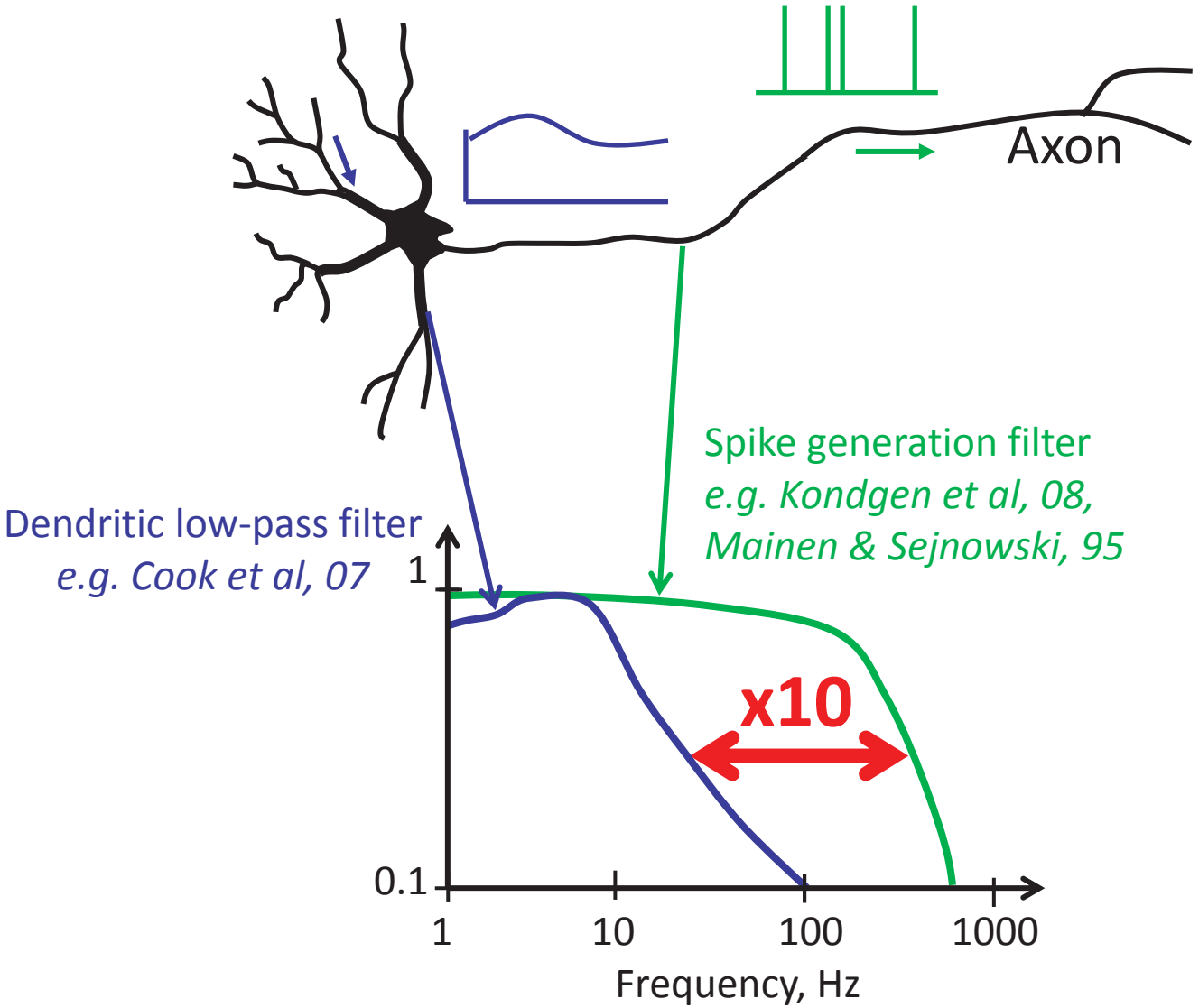




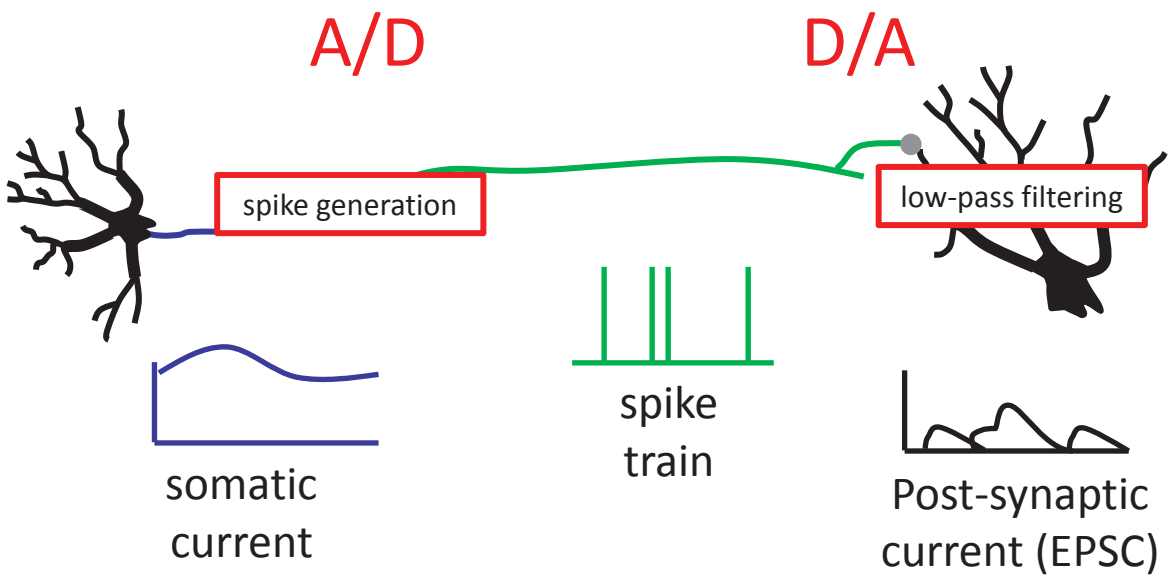


Adaptation of receptive fields can be modeled by optimal filters for different natural stimulus ensembles

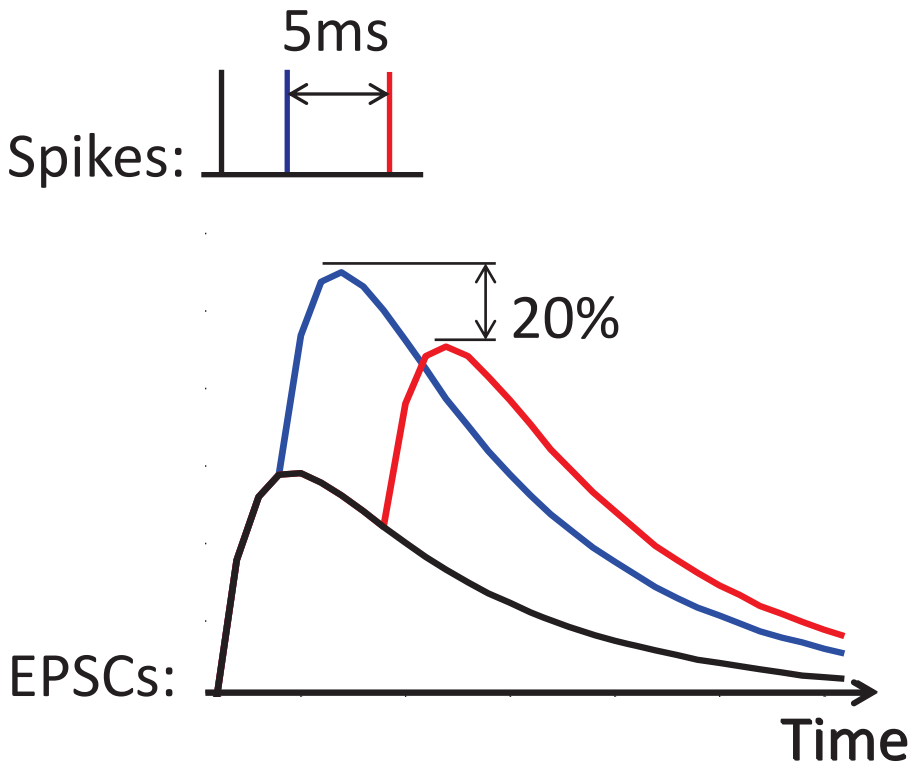
Mind the gap!


Axon
Spike generation filter
e.g. Kondgen et al, 08,
Mainen & Sejnowski, 95
Dendritic low-pass filter
e.g. Cook et al, 07
1
0.1
x10
1
10
100
1000
Frequency, Hz

Analog-Digital-Analog

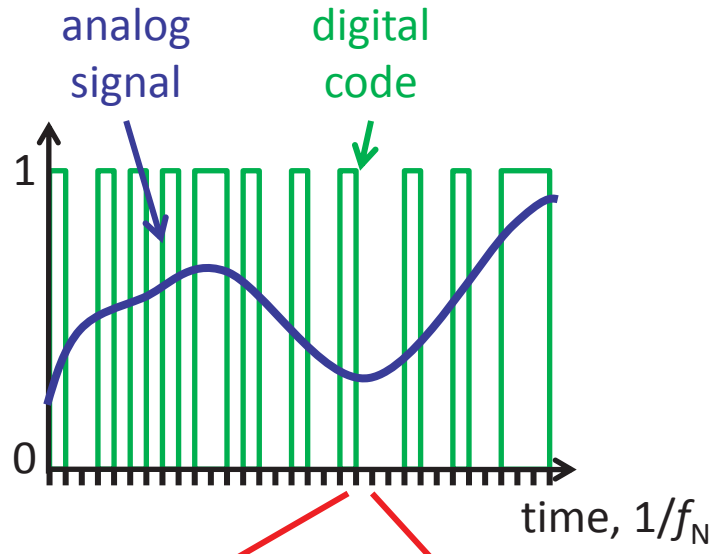


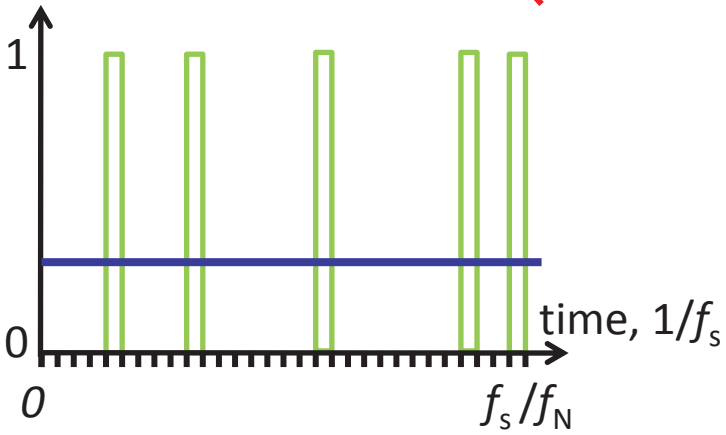
How can spike timing encode current amplitude?

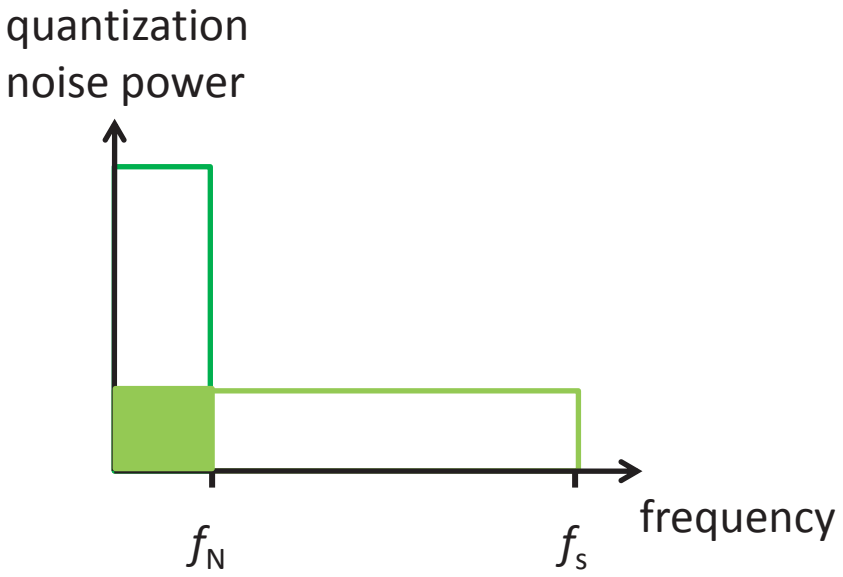


Over-sampling and noise-shaping

Poisson encoder: over-sampling



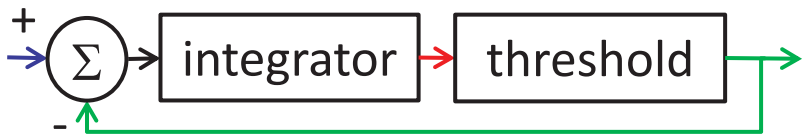


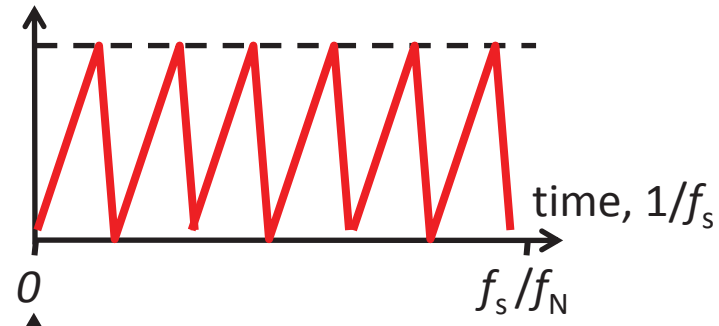


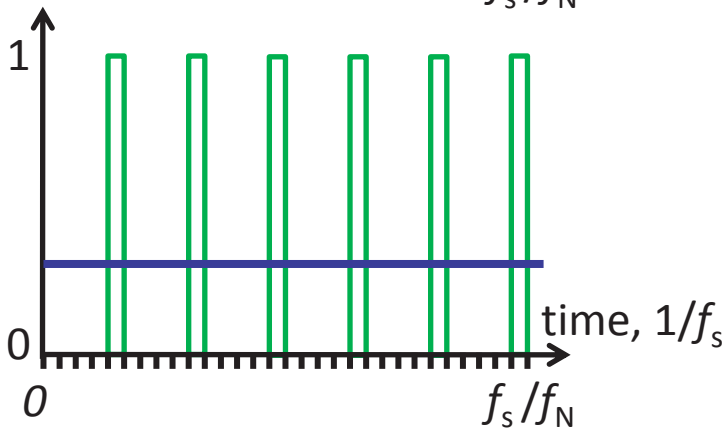
Nyquist rate, f_N
sampling rate, f_s
# of spikes ~ f_s/f_N
variance ~ f_s/f_N
<error^2> ~ variance/(# of spikes)^2 ~ f_N / f_s

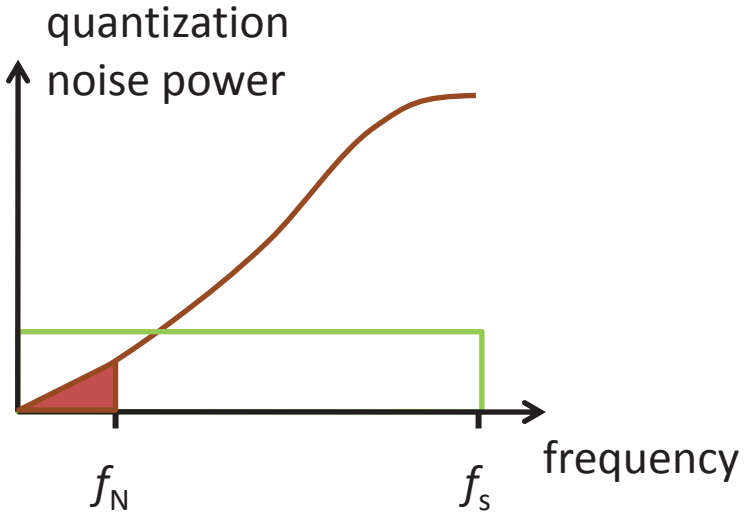
$\Delta\Sigma$ modulator: over-sampling & noise-shaping

a.k.a. Integrate-and-fire* (*Shin*)









Nyquist rate, f_N

sampling rate, f_s

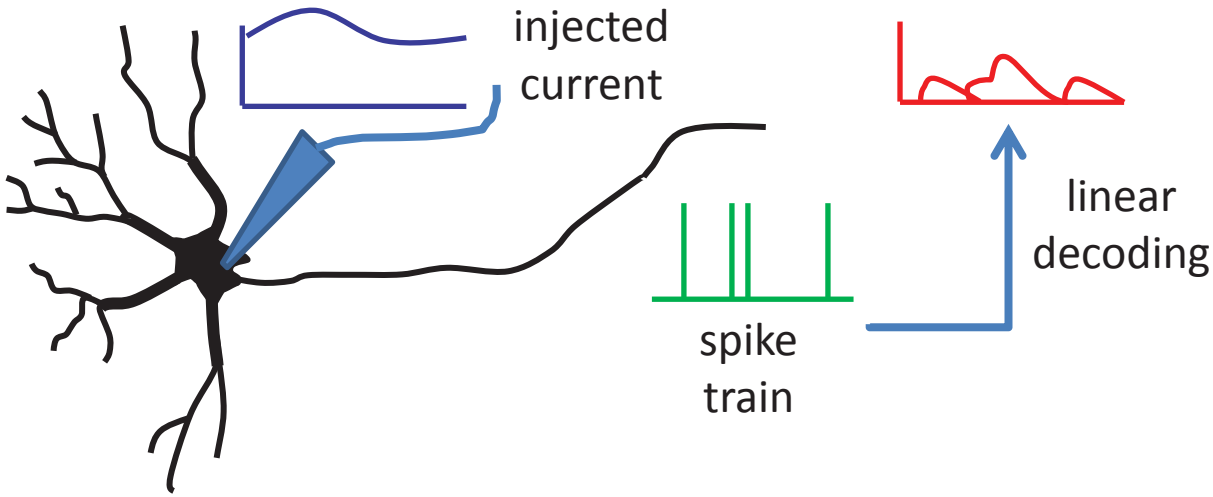
# of spikes ~ f_s/f_N

variance ~ 1

<error^2> ~ variance/(# of spikes)^2 ~

~ $(f_N / f_s)^2$

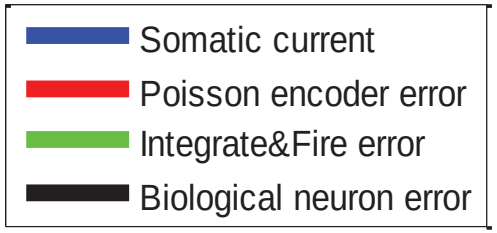
Experimental evidence of noise-shaping?



Datasets:

1. Ferret visual cortex neurons (*Wang & McCormick*)
2. Mouse olfactory mitral cells (*Tripathy & Urban*)
3. Fly olfactory receptor neurons (*Nagel & Wilson*)

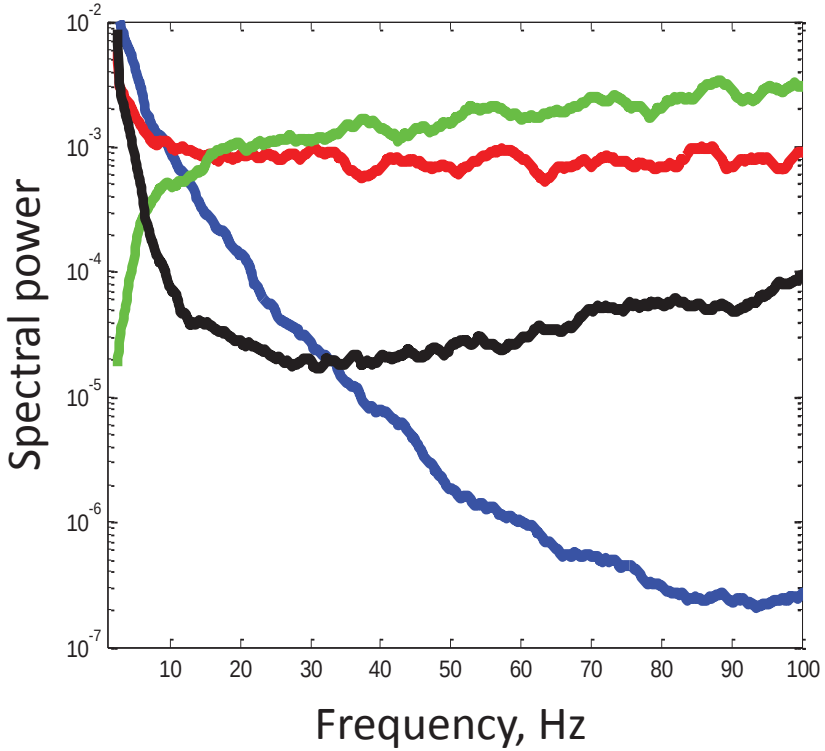
Experimental evidence of noise-shaping



somatic current

somatic current

spike train

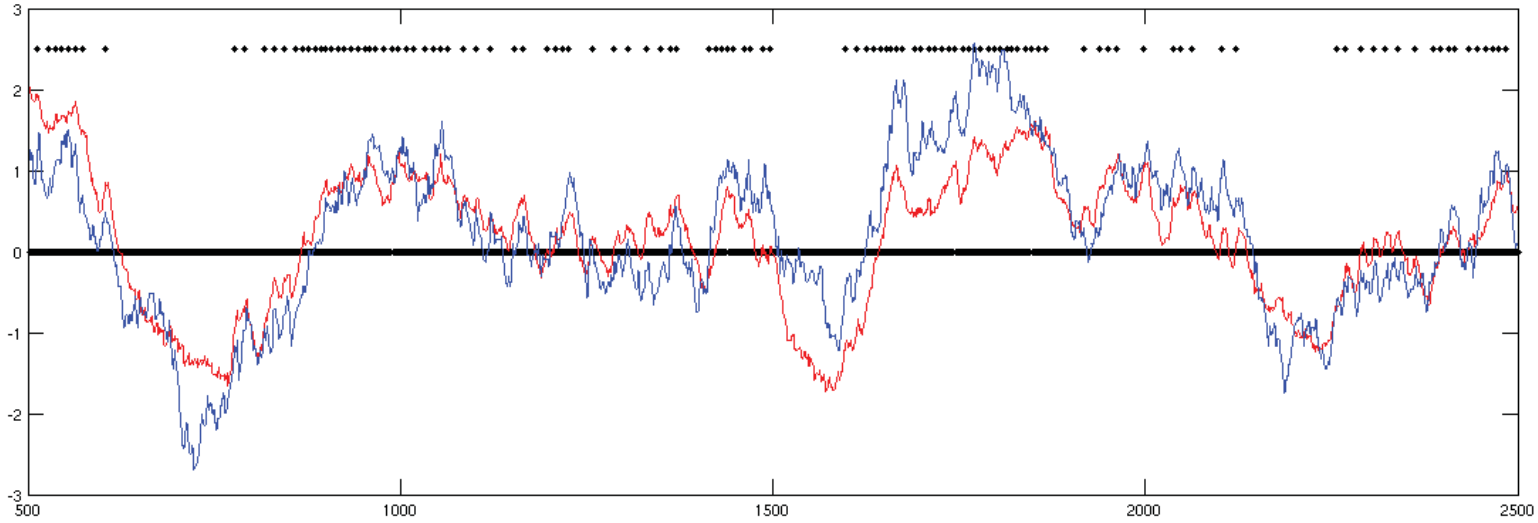


Linear decoding of spike trains

spike train

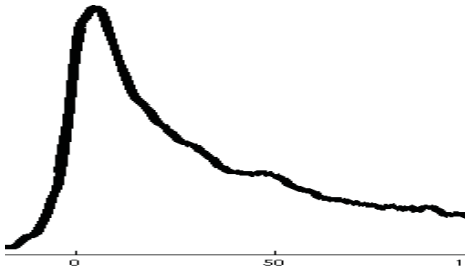
injected current

linear decoding



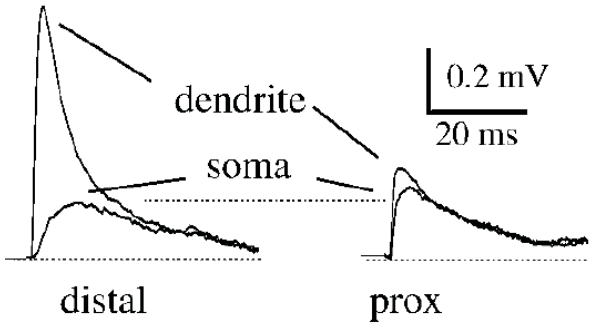
time, ms

Optimal linear filter



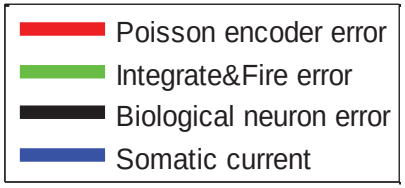
time, ms

Average EPSP



Magee & Cook, 2000

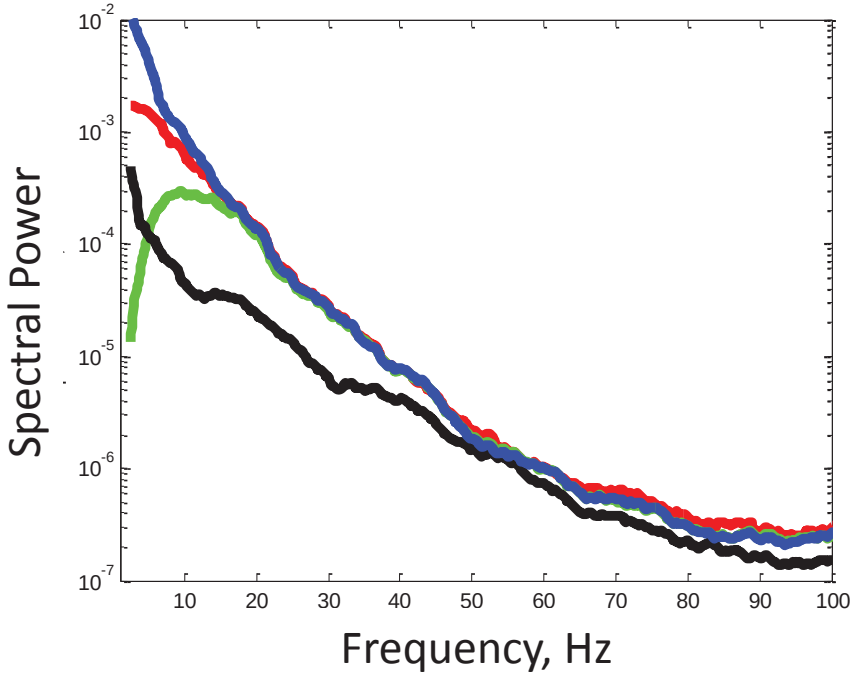
Decoded spike train error



somatic current

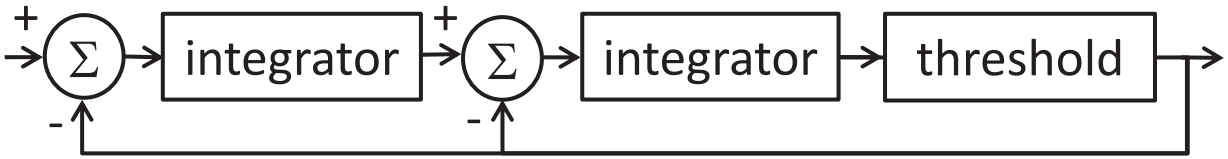
somatic current

decoded current



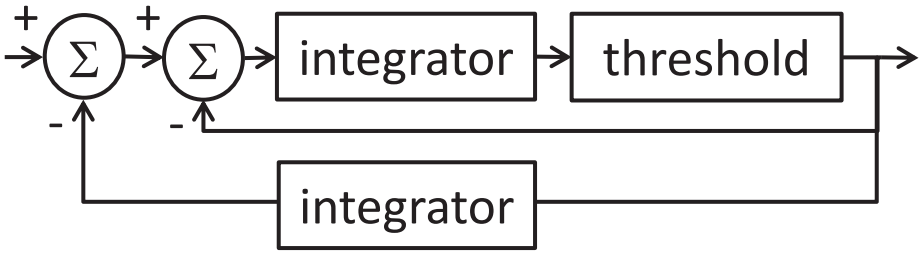
Advanced noise-shaping

- higher-order prediction: $\langle \text{error}^2 \rangle \sim (f_N / f_s)^5$

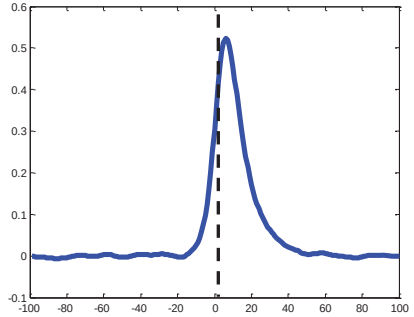


Response to constant current injection:

- $\Delta\Sigma$ combined with predictive coding:



Optimal decoding filter



Time lag

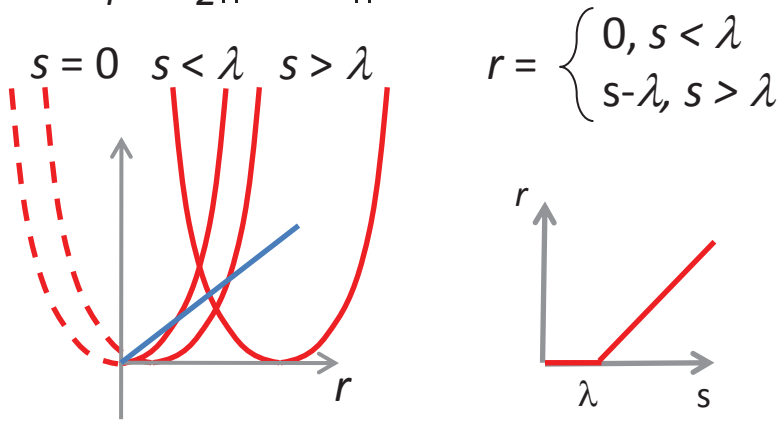
View the zoo of ion channels as non-linear predictors and integrators

Why rectification?

- Energy efficiency (*Laughlin, Levy, Lennie*)

  $\min[\langle \text{error}^2 \rangle + \lambda\ (\#\ \text{of spikes})]$

  $\min_r\ {}^1\!/_2 \|s - r\|^2 + \lambda\, r$



- De-noising:

  Threshold-linear function finds most probable signal estimate for Laplacian signal and Gaussian noise

Acknowledgements

Arjun Bharioke

Shaul Druckmann

Tao Hu

Karol Gregor

Ziqiang Wei

Neural coding

Daniel Soudry