Anticipative Dynamics in an Adaptive Excitable System

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Contents

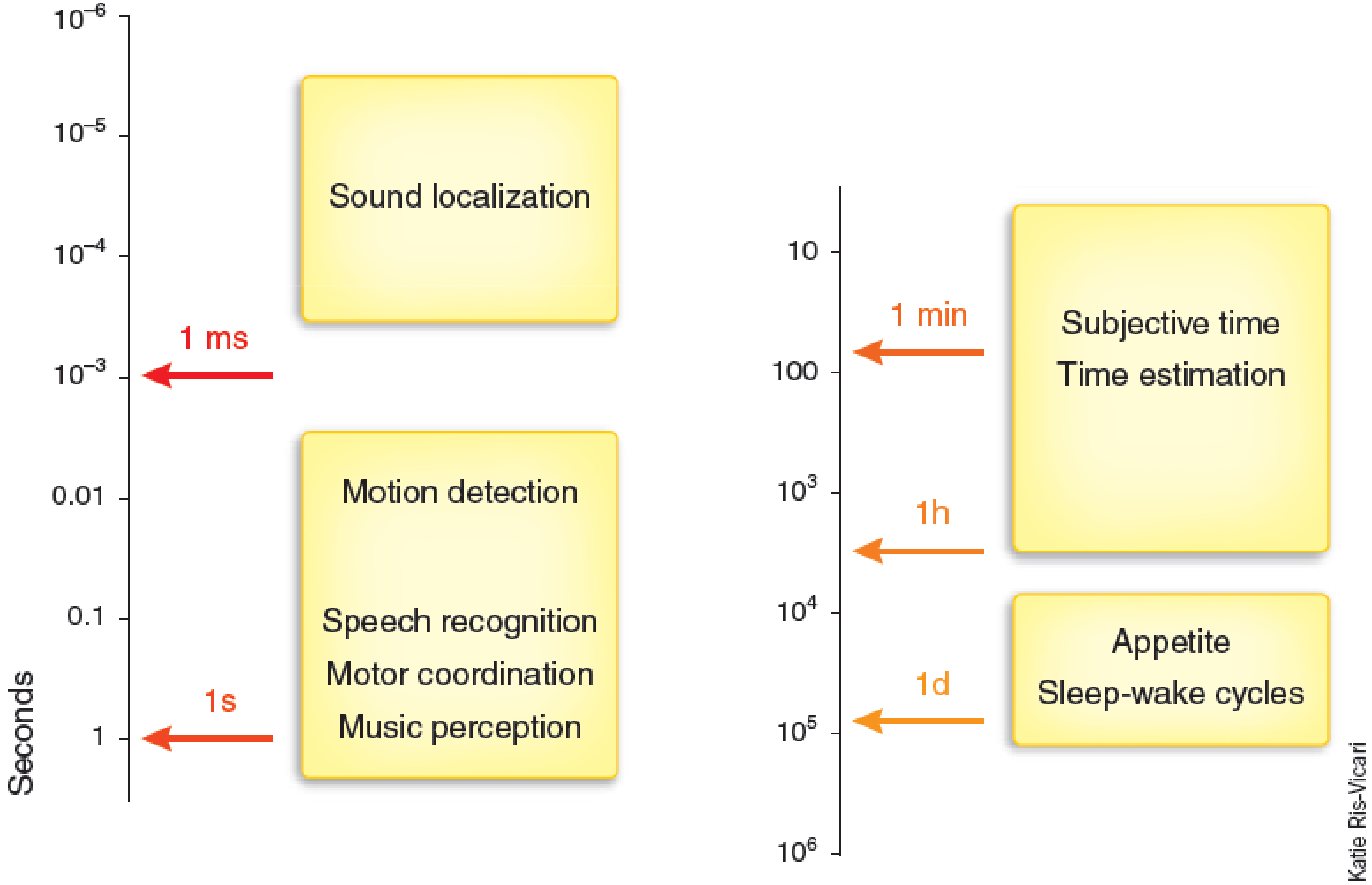
- Anticipation, predictive coding and some examples
- Clock and intrinsic oscillation Models
- Adaptable excitable system as an “entrainable” oscillator with anticipative dynamics (FHN)
- Synaptic mechanism for anticipative dynamics (TM)
- Conclusions:

  no central clock is needed

  anticipative dynamics is an adaptation

  time – sensed by entrained reverberations with STSP

Biological Time Scale



Buonomano VOLUME 3 NUMBER 10 OCTOBER 2007 NATURE CHEMICAL BIOLOGY

How do robots perceive the external world?

Stimuli	**Example of Sensor**	**Effects**
Temperature/Heat	Thermistor	Resistance
Chemicals	Spectral line absorption calculation	Number translator into voltage or current
Mechanical Stress	Piezoelectric device	Voltage
Light	Photo-Diode	Current
Time	Clock/Counter	Triggered Events

How do we perceive the external world?

Stimuli	Example of Sensor	Effects	Buddism
Temperature/Heat	transient receptor potential ion channel	Membrane potential Chemical release	Body
Chemicals	Ca, Na, K channels	Membrane potential Chemical release	Taste/Odor
Mechanical Stress	mechano-gated potassium channels	Membrane potential Chemical release	Sound/Touch/Body
Light	Light-gated ion channels Rhodopsin	Membrane potential Chemical release	Sight
Time	???	Anticipation	Mind / Pains?

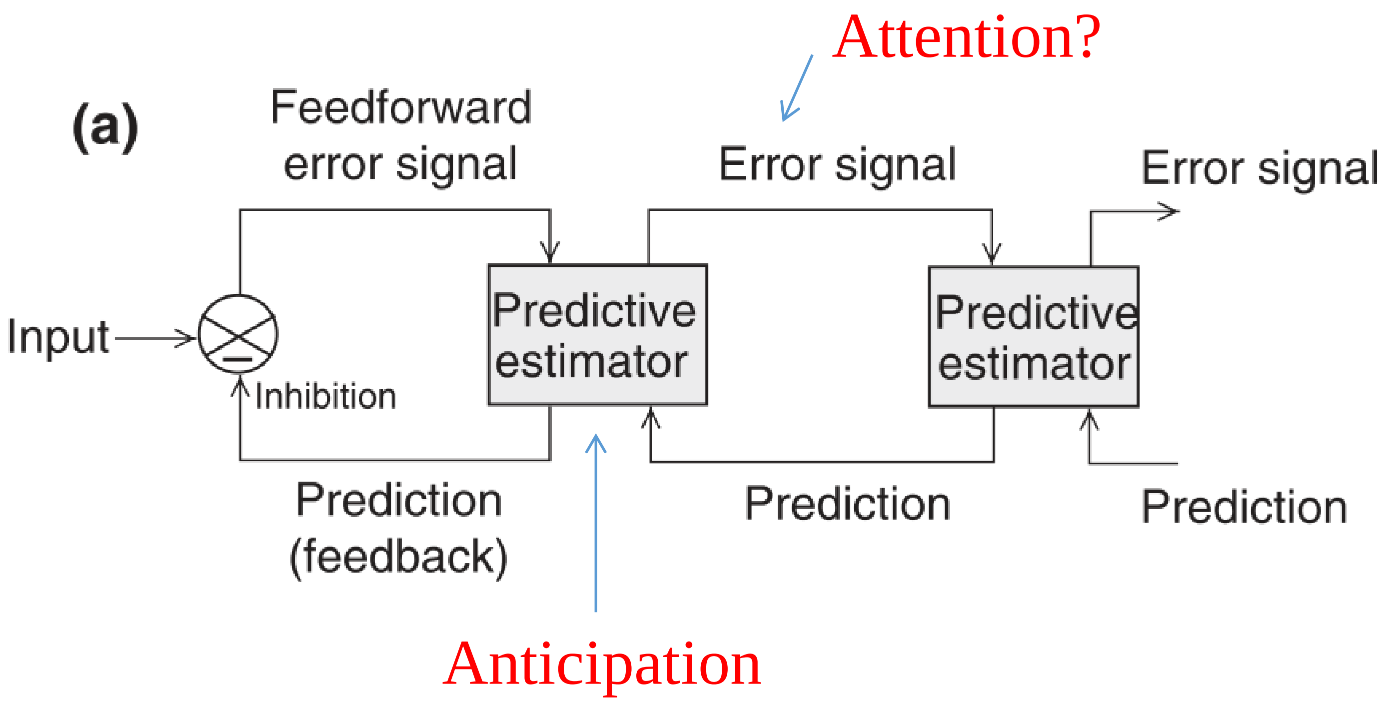
Weak and strong anticipation

- Weak anticipation: the analytic method predicts an explicitly referenced future with an internal model
- Strong anticipation refers to an anticipation of events generated by the system itself

Dubois 2000a

Predictive Coding and anticipation

- Minimize processing resources
- Focus only on changes

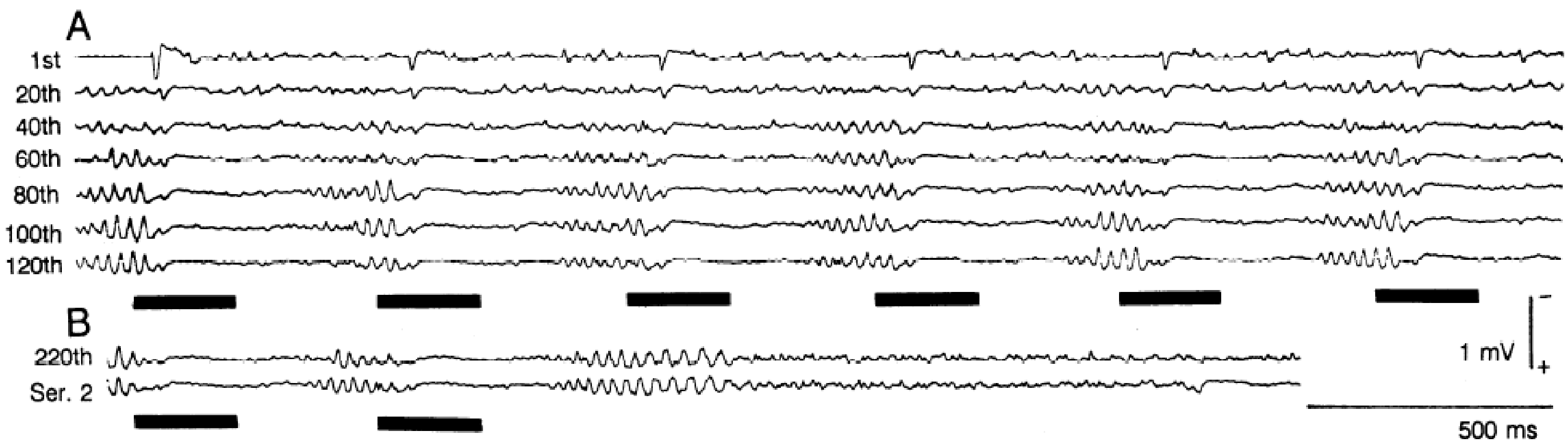


Rao et al. Wiley Interdisciplinary Reviews-Cognitive Science 2(5): 580-593.

Event-Related Potentials in the Retina and Optic Tectum of Fish

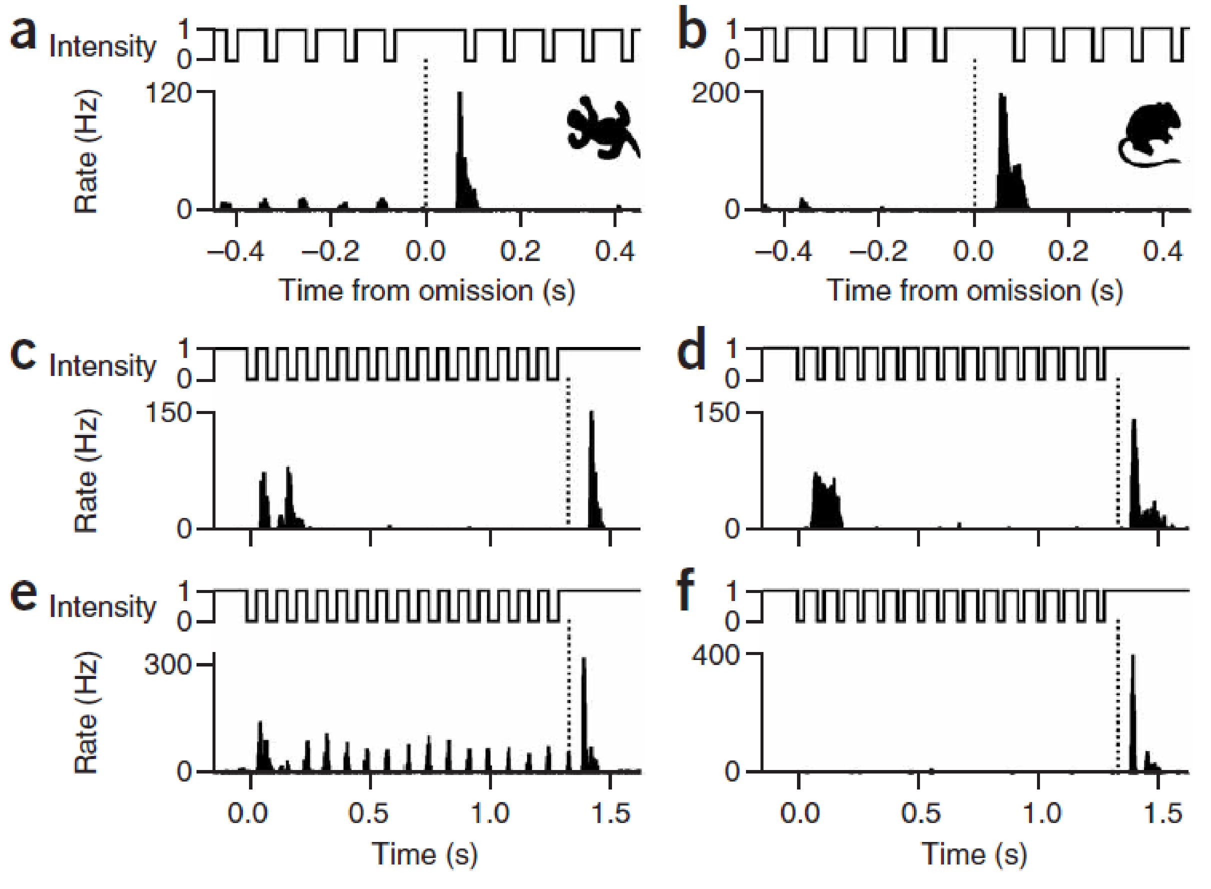
THEODORE H. BULLOCK, MICHAEL H. HOFMANN, FREDERICK K. NAHM,
JOHN G. NEW, AND JAMES C. PRECHTL

- Compound field potential measured in optic tectum from elasmobranchs and teleosts.
- Diffuse light flashes →Event-related potentials



JOURNAL OF NEUROPHYSIOLOGY
Vol. 64, No. 3, September 1990. *Printed in U.S.A.*

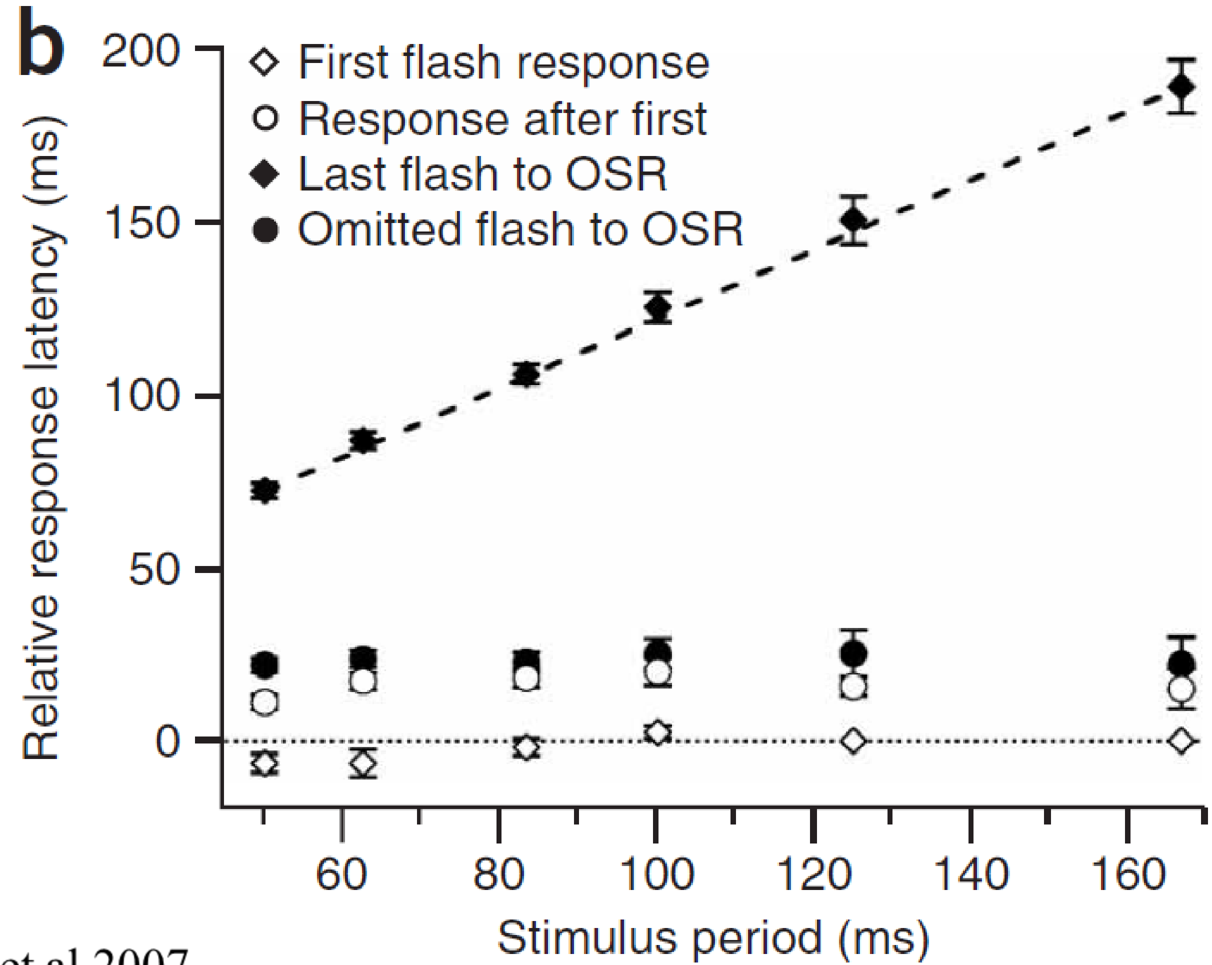
Detection and prediction of periodic patterns by the retina



Schwartz et al 2007

VOLUME 10 | NUMBER 5 | MAY 2007 NATURE NEUROSCIENCE

OSR encoded in stimulation



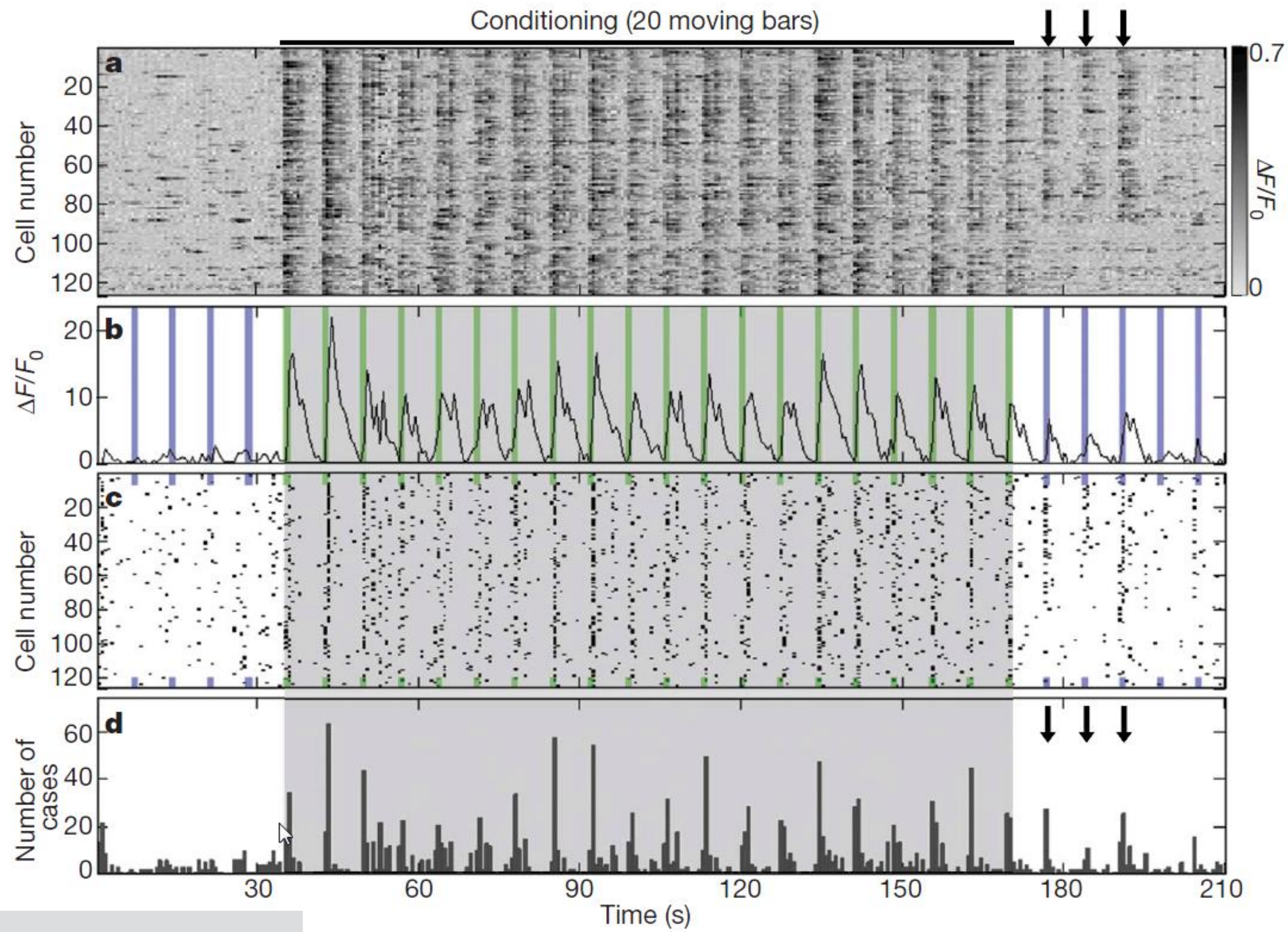
Schwartz et al 2007

Entrained rhythmic activities of neuronal ensembles as perceptual memory of time interval

Germán Sumbre[1]†, Akira Muto[2], Herwig Baier[2] & Mu-ming Poo[1]

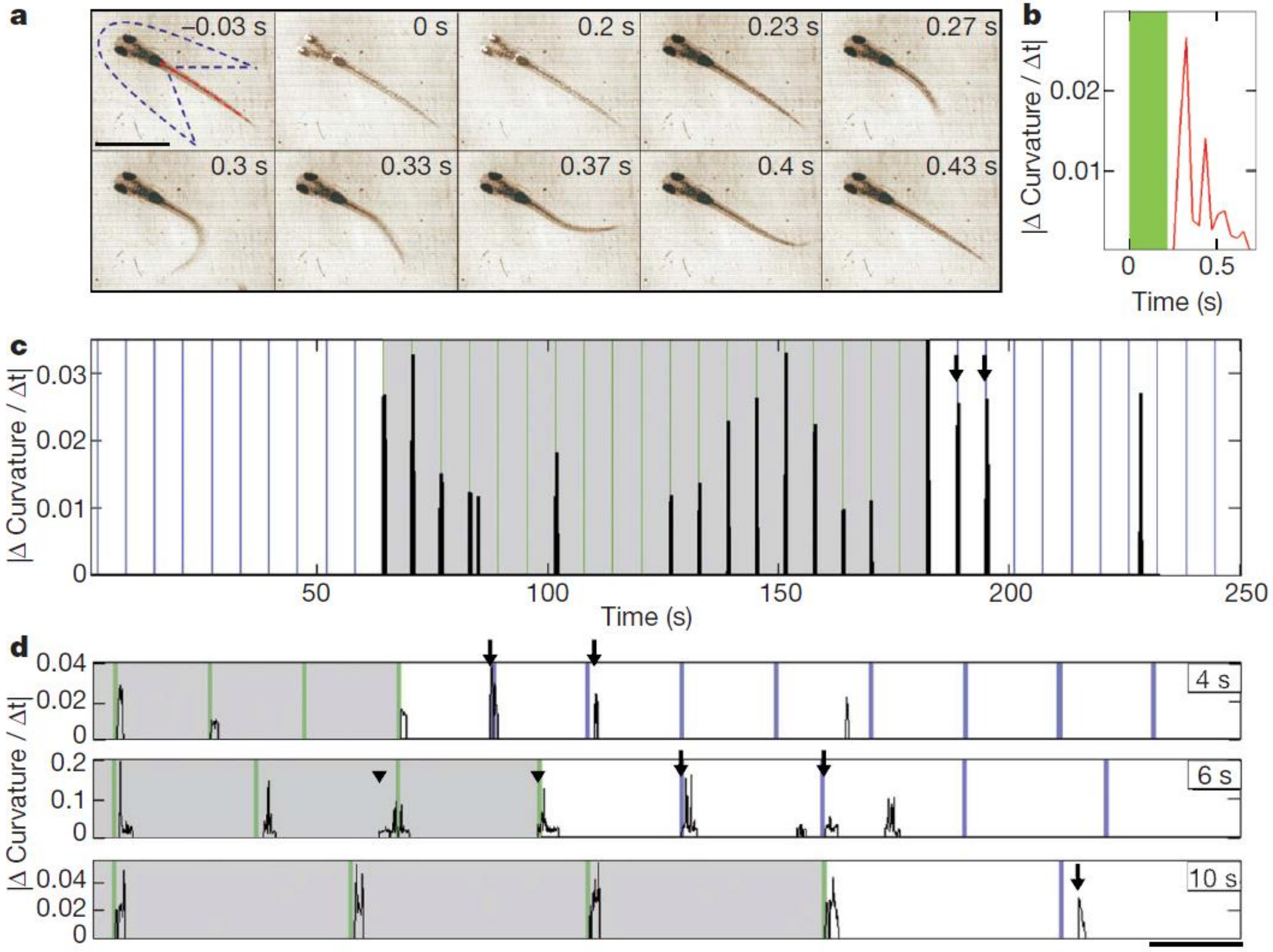
Ca transients in zebrafish optic tectum

Moving bar conditioning



Vol 456 | 6 November 2008 | **doi:10.1038/nature07351**

Evoked motions



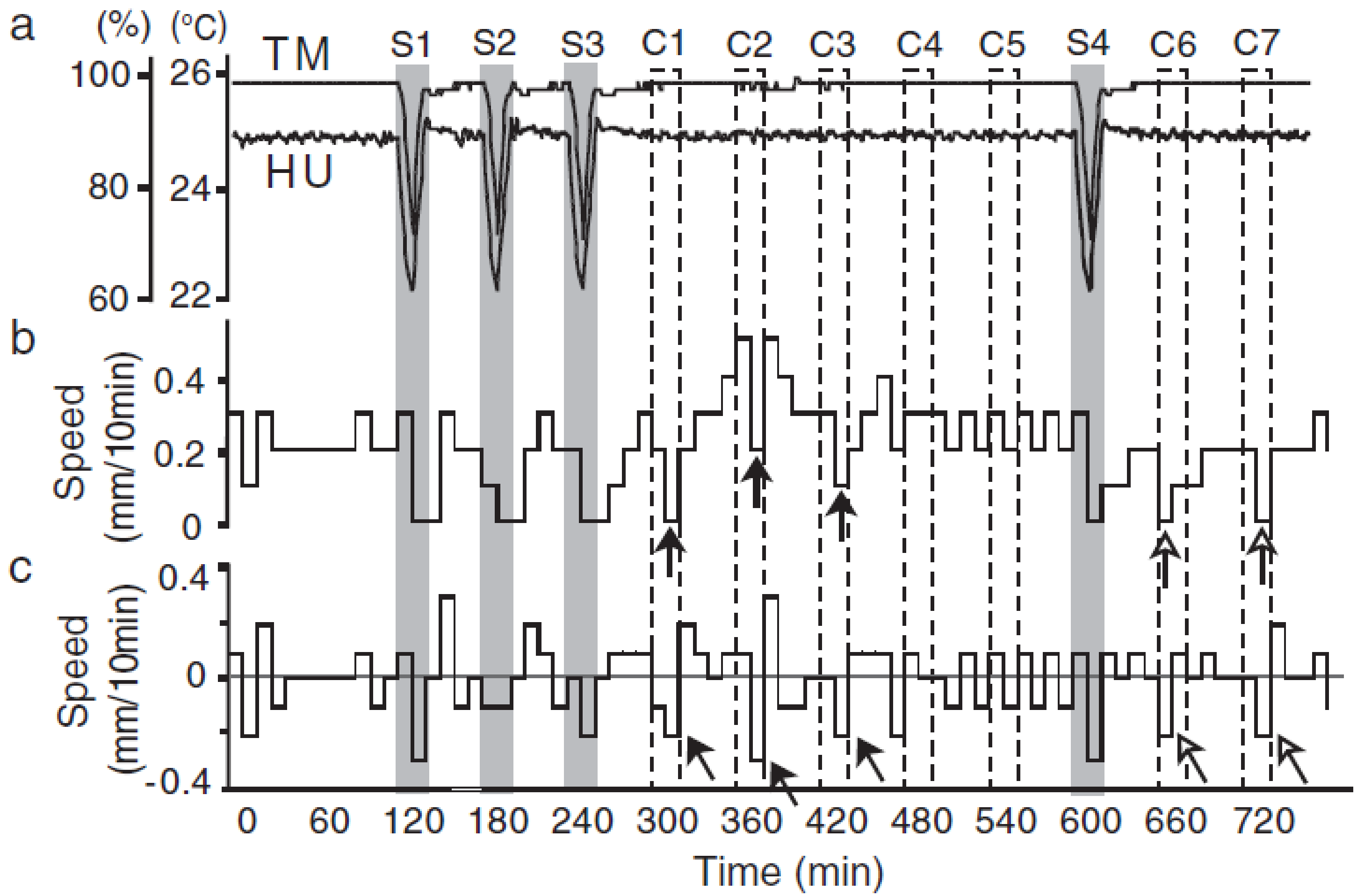
Amoebae Anticipate Periodic Events

- slime mold Physarum were exposed to unfavorable conditions presented as three consecutive pulses
- reduced locomotive speed in response to each episode.
- subsequently subjected to favorable conditions, spontaneously reduced their locomotive speed at the time when the next unfavorable episode would have occurred.

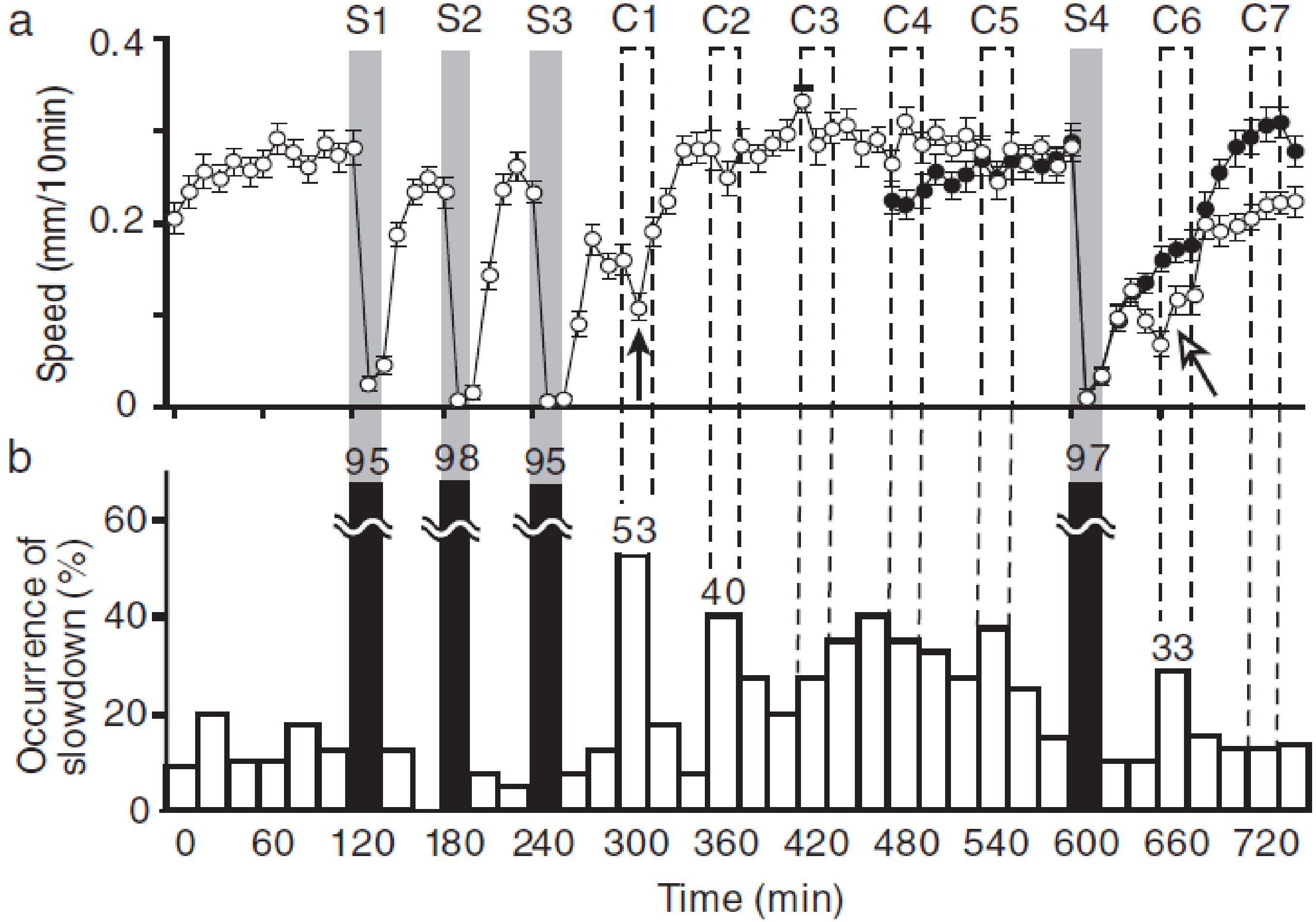
Tetsu Saigusa et al

PRL **100,** 018101 (2008)

Expt with temperature stimulation



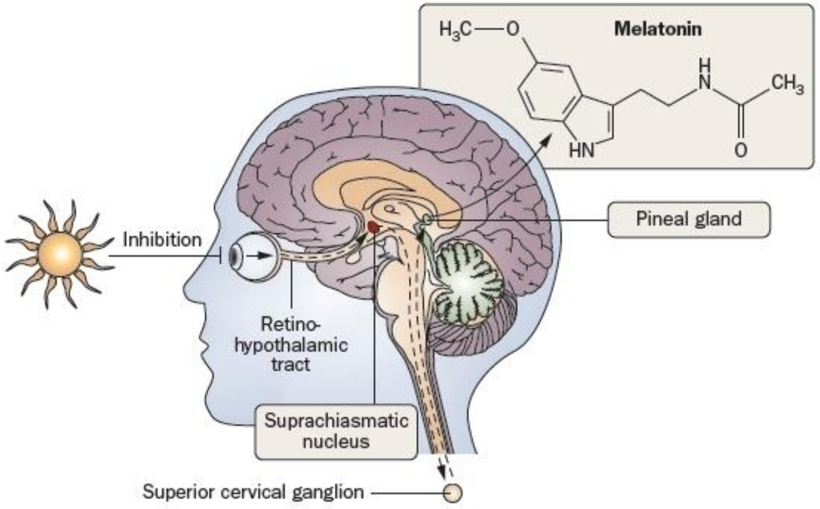
Statistical Analysis



The Clock Model

Centralized and specialized circuit
Suprachiasmatic nucleus

68000 timing



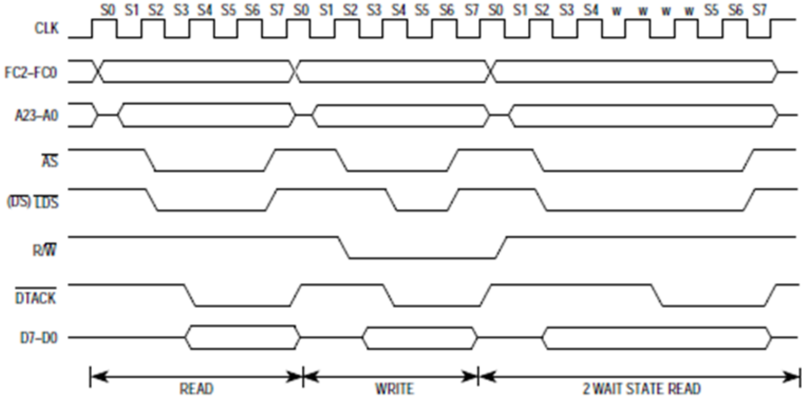


Figure 4-2. Read and Write-Cycle Timing Diagram

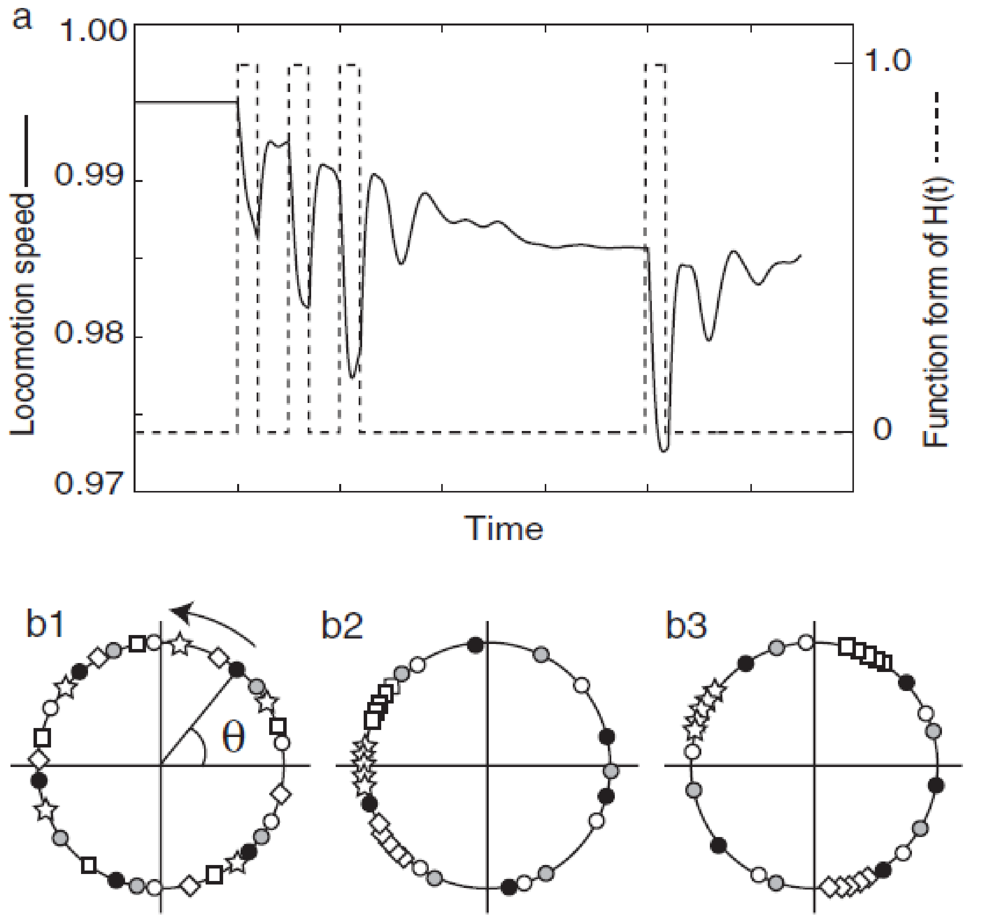
Source: Nat Rev Nephrol © 2009 Nature Publishing Group

http://www.bigmessowires.com/2011/08/

Phase Model

$$\frac{d\theta_{i,j}}{dt} = \omega_j + \alpha H(t) \sin(2\pi\theta_{i,j}) + \xi_{i,j},$$

$$S = \sum_j \tanh\left(2 \sum_i^N \frac{\cos 2\pi\theta_{i,j}}{N} + 3\right),$$



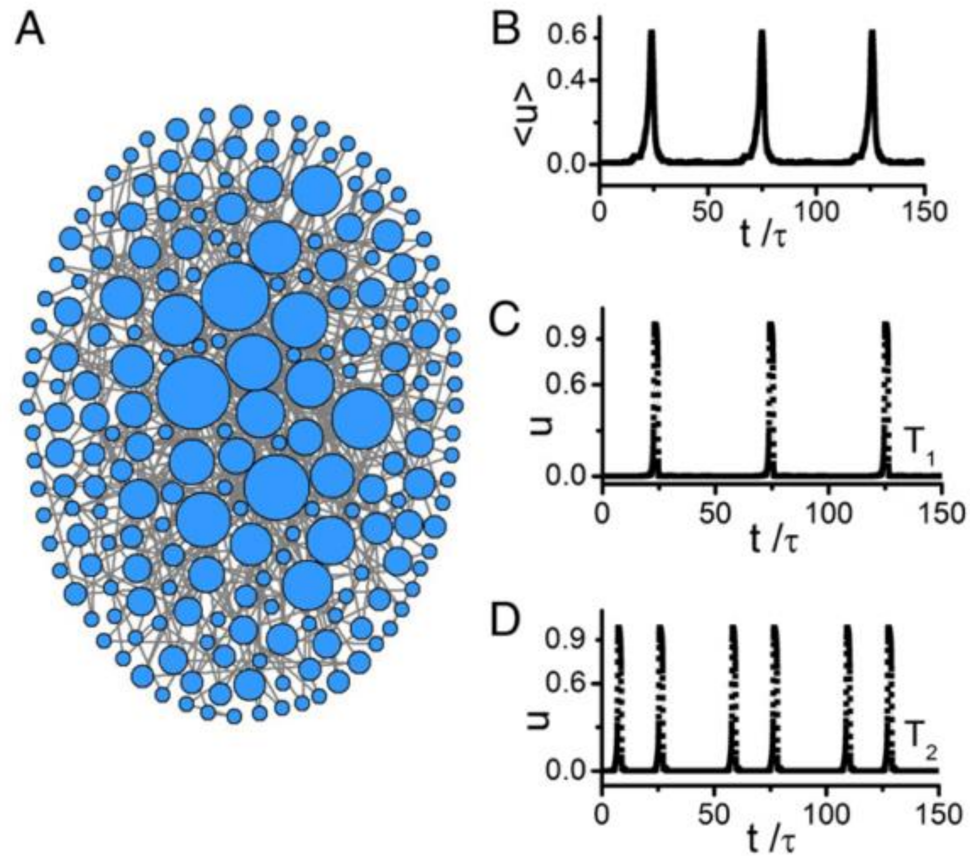
Tetsu Saigusa et al

PRL **100,** 018101 (2008)

Long-period rhythmic synchronous firing in a scale-free network

$$\frac{du_i}{dt} = -\frac{1}{\epsilon}u_i(u_i - 1)\left(u_i - \frac{v_i + b}{a}\right) + \sum_{j\neq i}^{N} F_{ij},$$

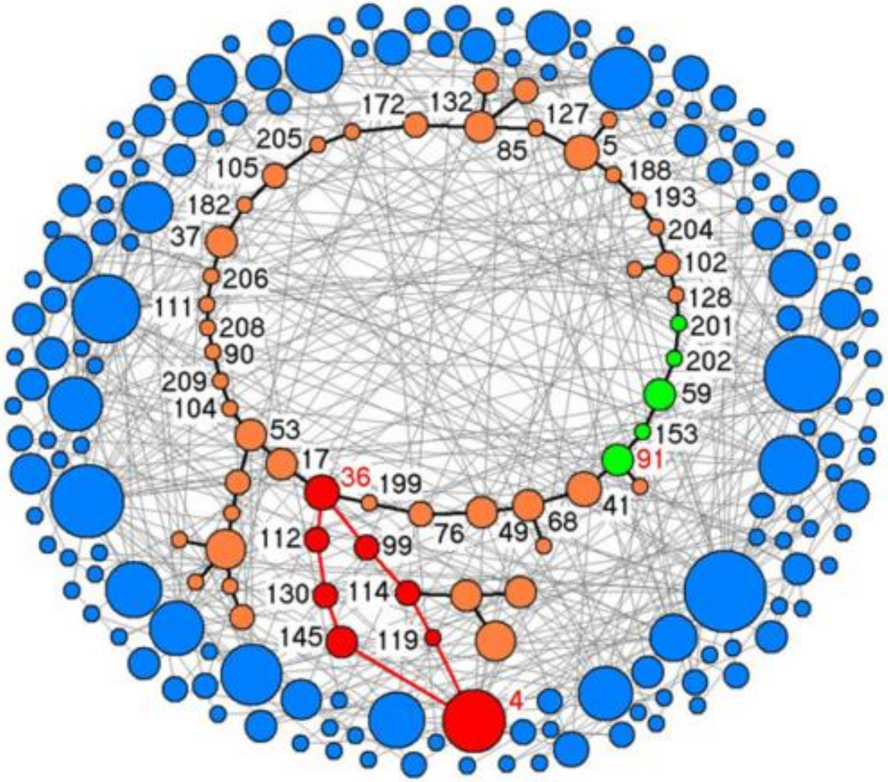
$$\tau\frac{dv_i}{dt} = f(u_i) - v_i,$$



Mi et al 2013

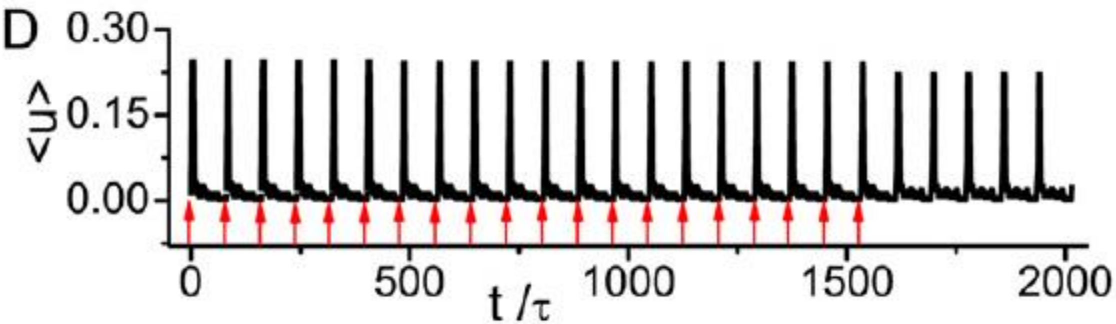
PNAS | Published online November 25, 2013 | E4931–E4936

E



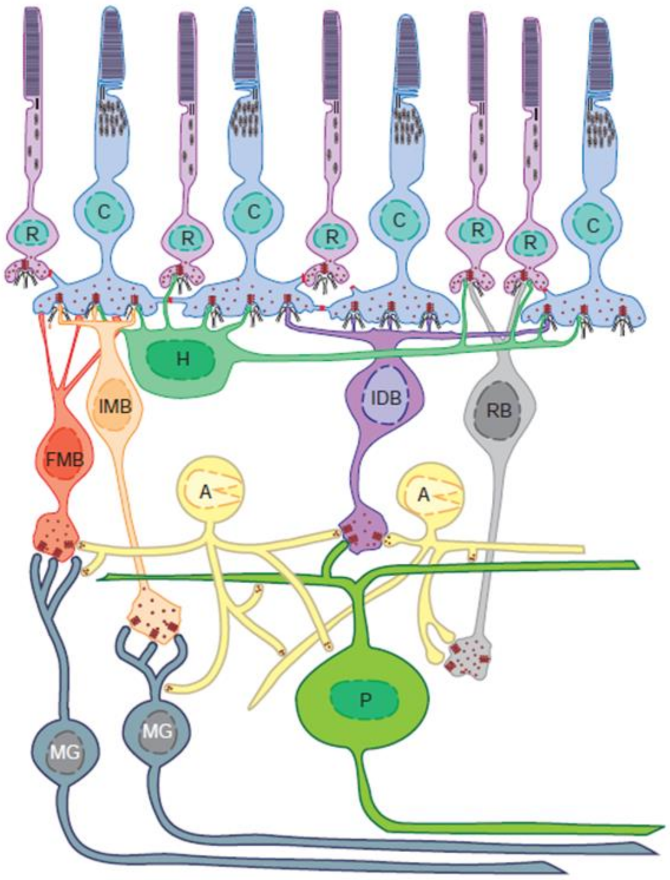
172
132
127
205
85
5
105
188
182
193
204
37
102
206
128
111
201
208
90
202
209
59
104
153
53
17
36
91
199
41
112
99
76
49
68
130
114
145
119
4

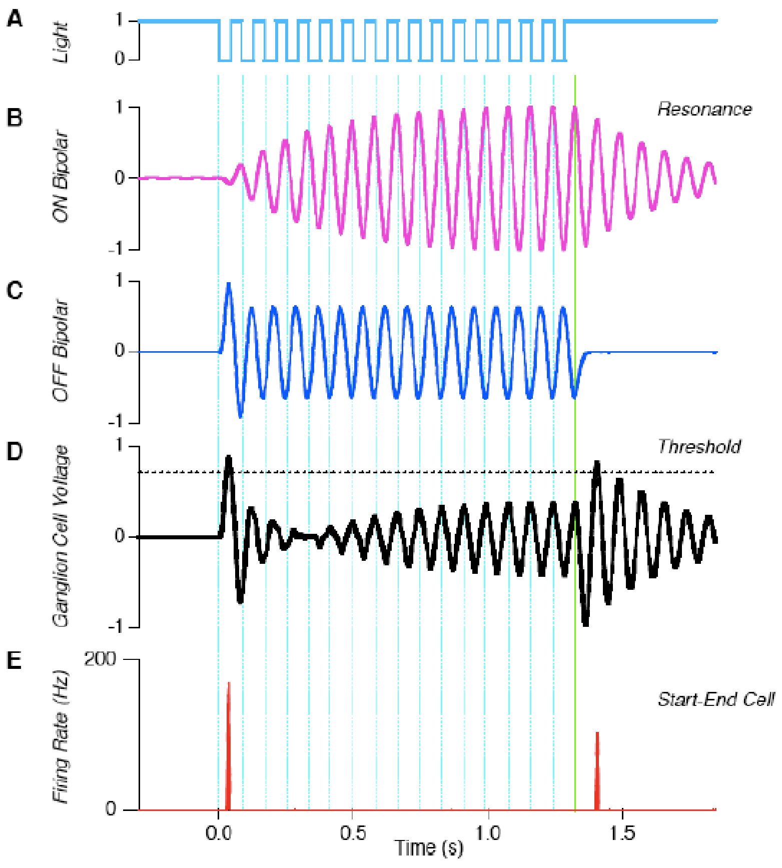
D



0.30
0.15
0.00
<u>
0
500
1000
1500
2000
t /τ

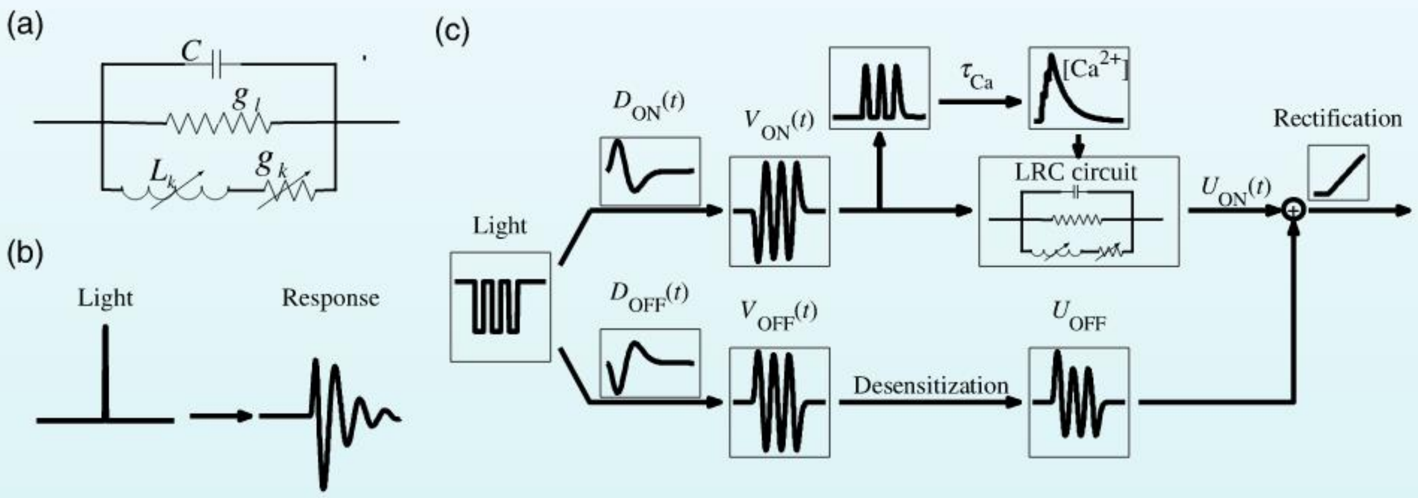
Intrinsic Oscillation Model





Schwartz, Ph.D. Thesis (2008)

Filter Model



$$U_{\mathrm{OFF}} = \begin{cases} -\bar{V}\int_0^t s(\tau)D_{\mathrm{ON}}(t-\tau)d\tau, & t \leq \tau_p \\ -0.7\bar{V}\int_0^t s(\tau)D_{\mathrm{ON}}(t-\tau)d\tau, & t > \tau_p \end{cases}$$

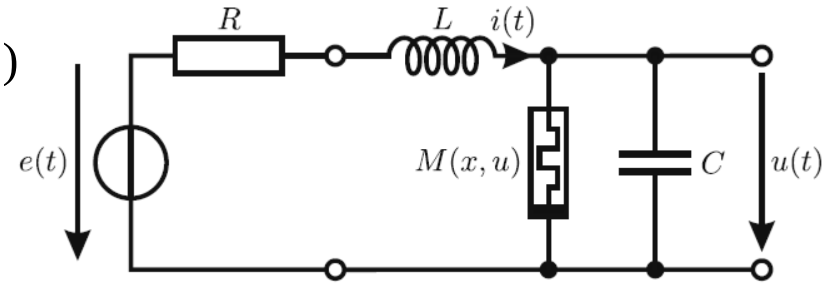
$$C\ddot{U}_{\mathrm{ON}} + \left[\frac{C}{L_k g_k} + g_l\right]\dot{U}_{\mathrm{ON}} + \left[\frac{g_k + g_l}{L_k g_k}\right]U_{\mathrm{ON}} = \dot{I} + \frac{I}{L_k g_k} .$$

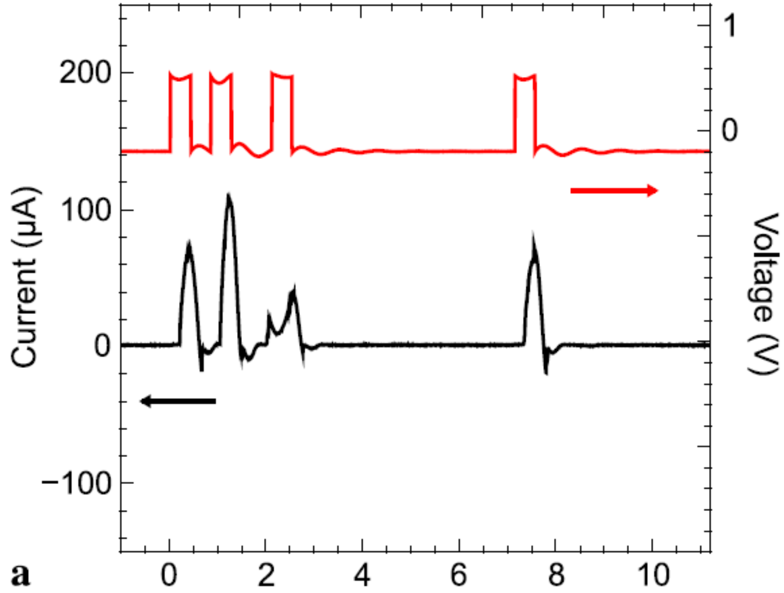
Linear ordinary differential equations with additional tuning mechanism

Gao et al 2009 Computation in Neural Systems

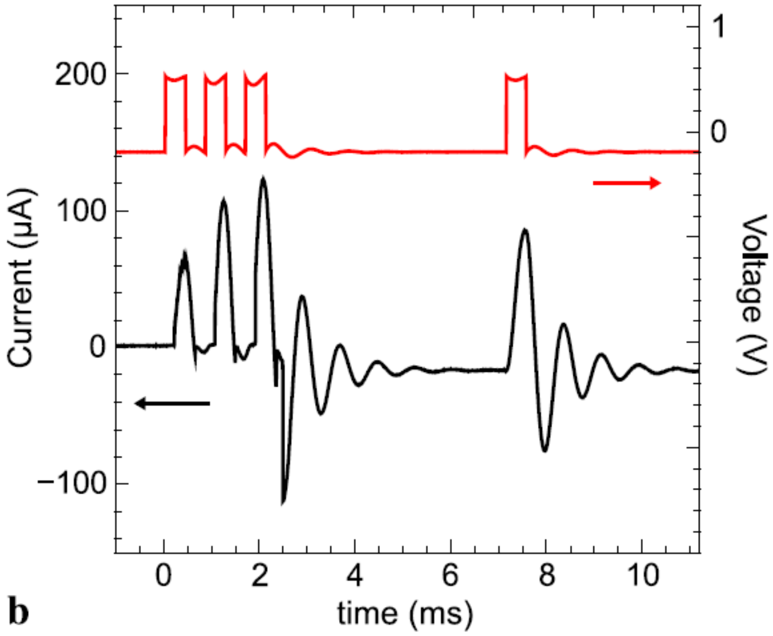
Learning of a memristor

- memory resistor (proposed, Chua 1971)
- History dependent resistor
- thin film TiO2 (HP Labs 2008)
- Adaptive Control





a



b

Ziegler et al 2014

Appl Phys A (2014) 114:565–570
DOI 10.1007/s00339-013-7615-5

Network State-dependent Model

- Non-localized
- Cerebellum, Cortical
- Inherently able to process time information
- Captured in the time-dependent state of the network
- Short term synaptic plasticity (Adaptation)
- Strong anticipation

Buonomano et al 2004

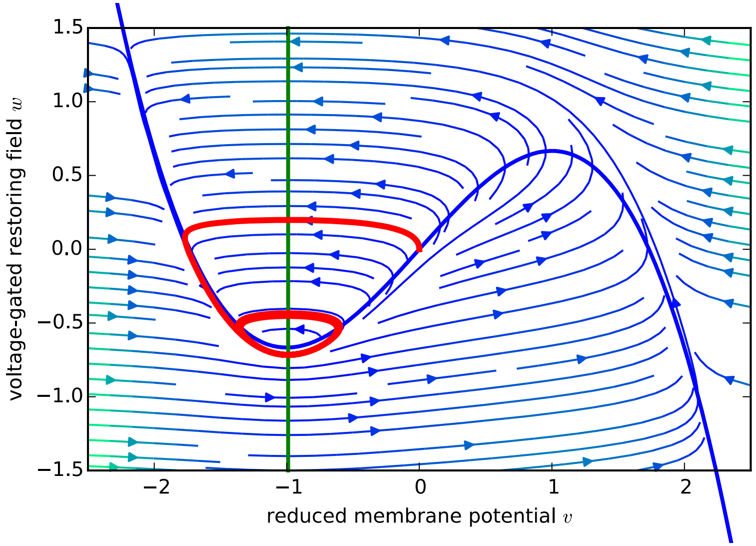
Annu. Rev. Neurosci. 2004. 27:307–40

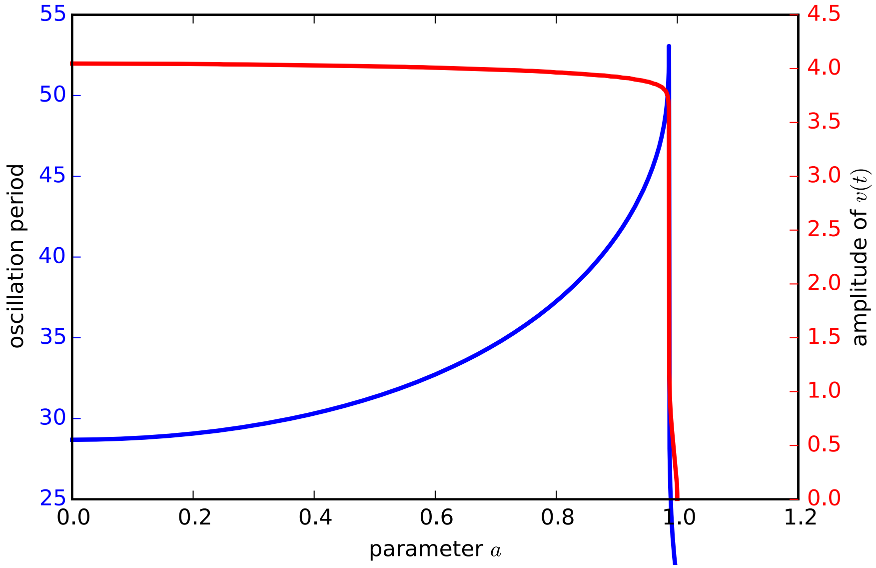
Adaptive Excitable System

FitzHugh-Nagumo Model

$$\frac{dv}{dt} = v - \frac{v^3}{3} - w + I_{ext}(t)$$

$$\tau_w \frac{dw}{dt} = v + a$$

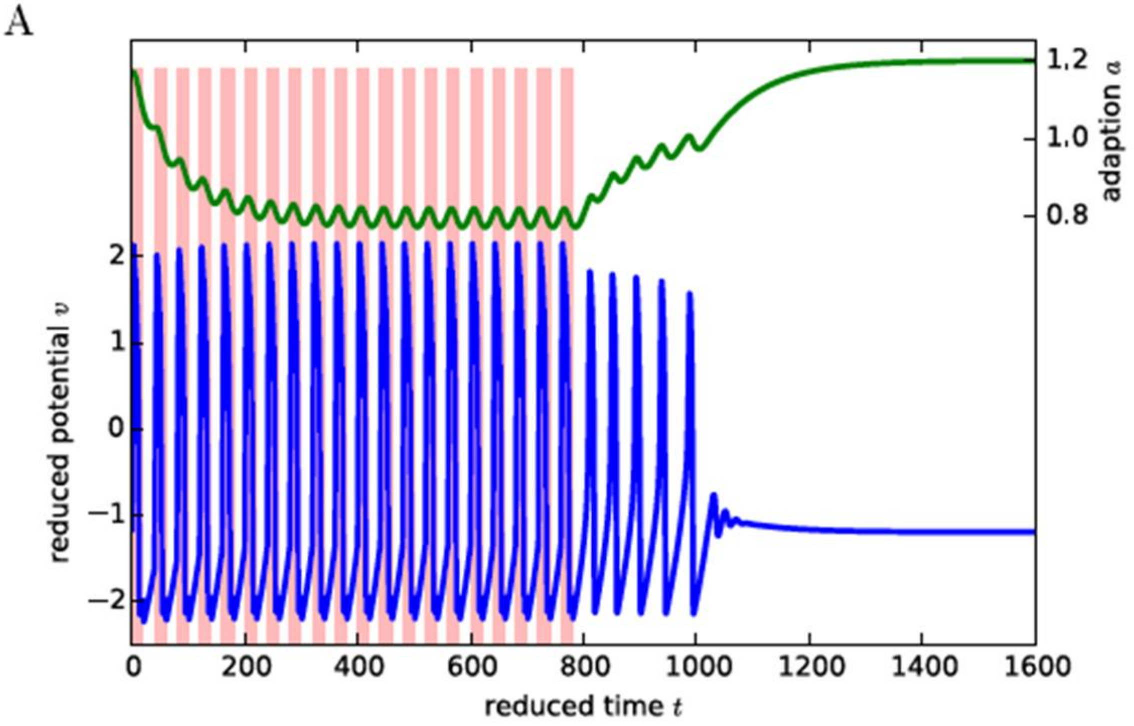




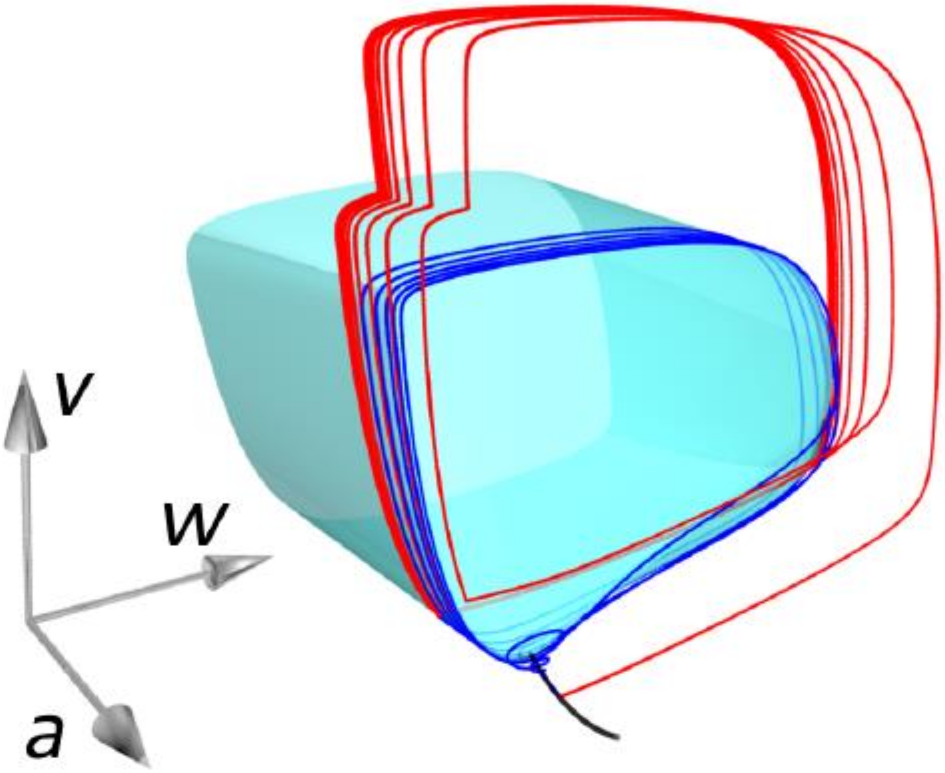
Adaptive Control of a

$$\frac{da}{dt} = \frac{1}{\tau_a}(\hat{a} - a)$$

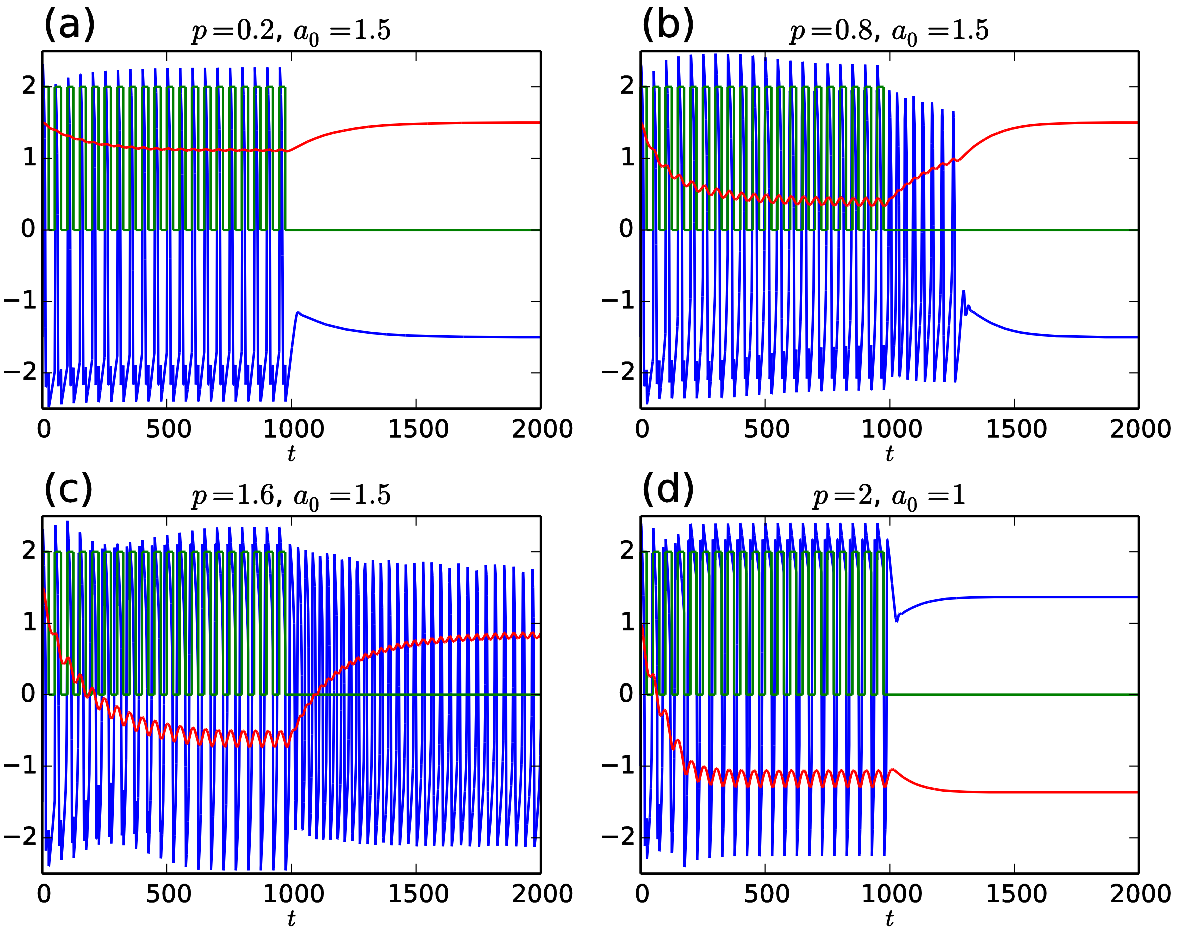
Entrained a



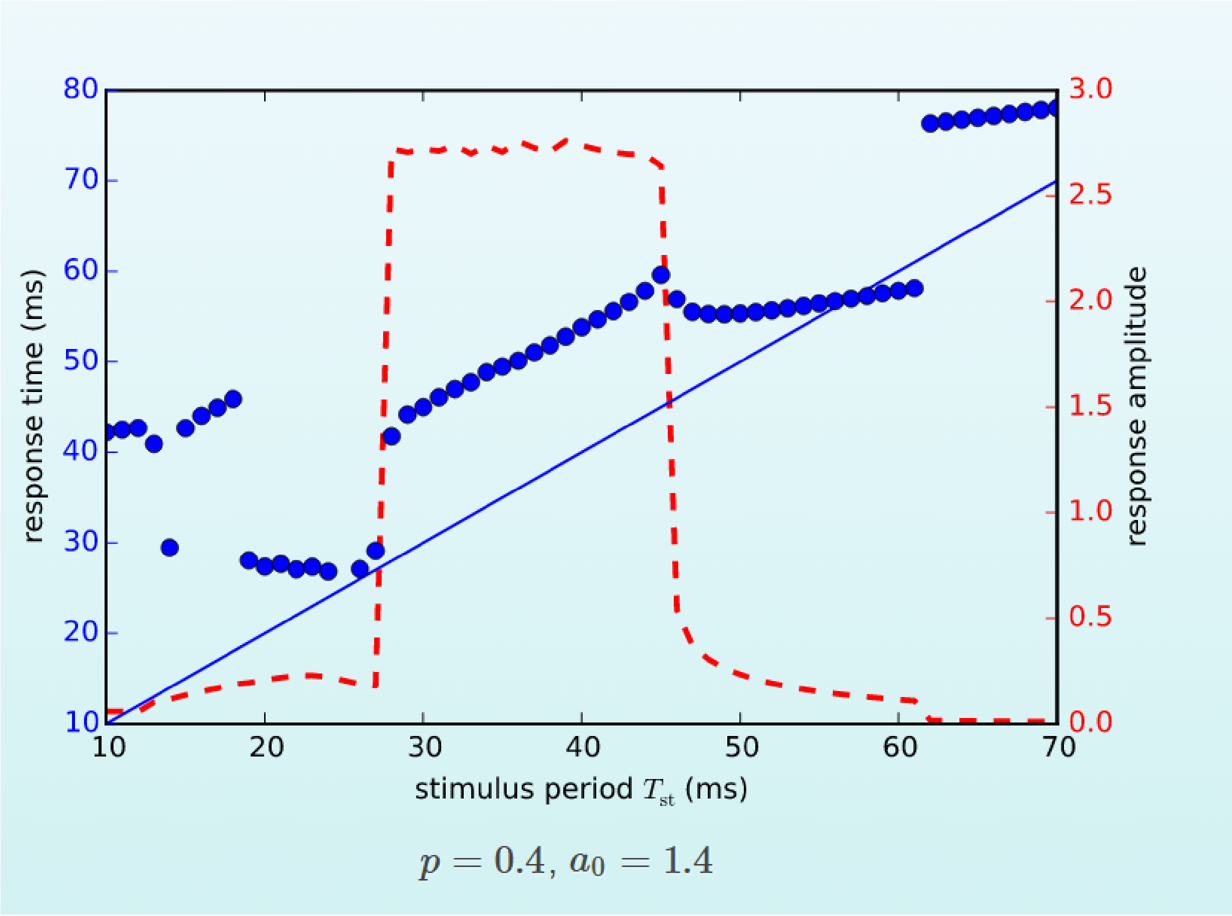
$$\frac{da}{dt} = \frac{\left[(1-p)a_0 + \frac{pa_0^3}{3}\right] - pw - a}{\tau_a}$$



Effects of different parameters



Optimal Retention of periodicity information



Network Spike and Single Cell Spike

Single cell Spike	Population Spike
Single Unit	Cooperative Phenomenon
Depolarization (Action Potential)	Bursting
A few ms	100ms ~ 1000ms
Excitability (Na)	Short Term Synaptic Plasticity Recurrent Connectivity
Refractoriness (K)	Depletion of neural transmitters
Repolarization	Recovery of neural transmitters

TM Model

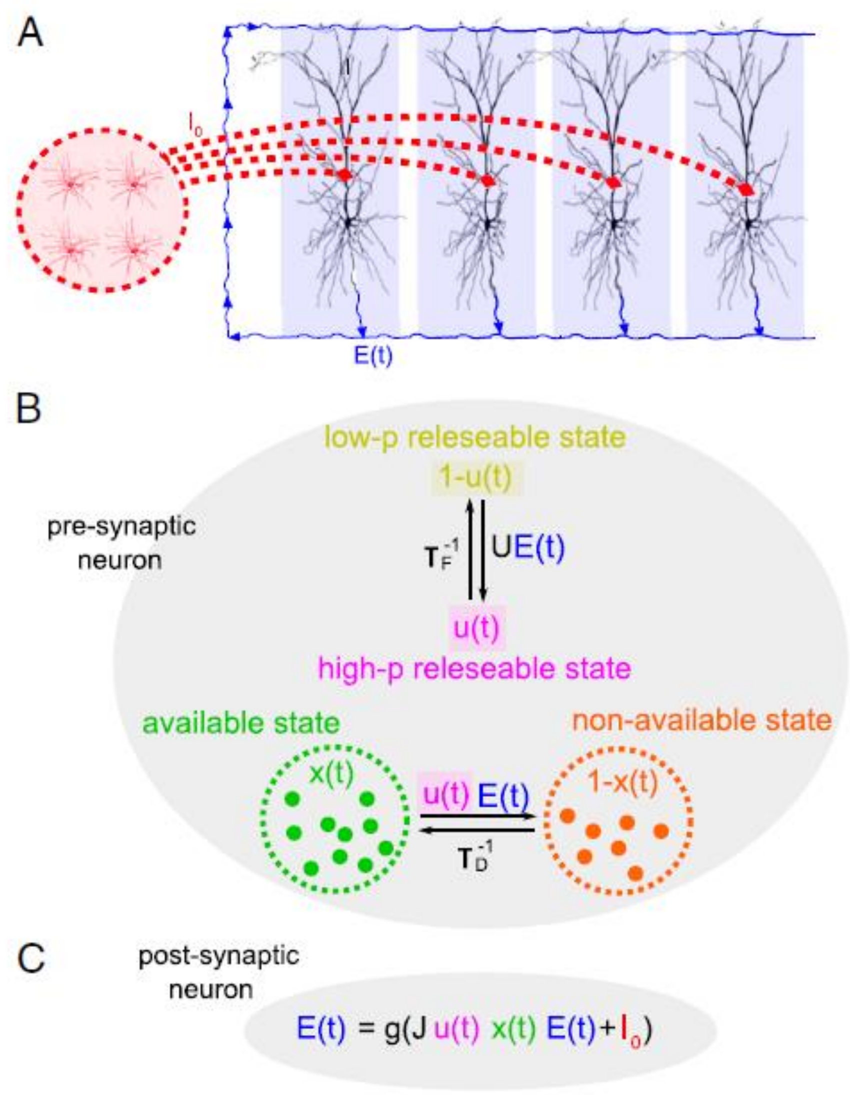
$$\frac{dE}{dt} = \frac{1}{\tau}\left[-E + \alpha \ln\left(\frac{1 + e^{\frac{JuxE+I}{\alpha}}}{2}\right)\right]$$

$$\frac{dx}{dt} = \frac{1-x}{\tau_D} - uxE$$

$$\frac{du}{dt} = \frac{U-u}{\tau_F} + U(1-u)E$$

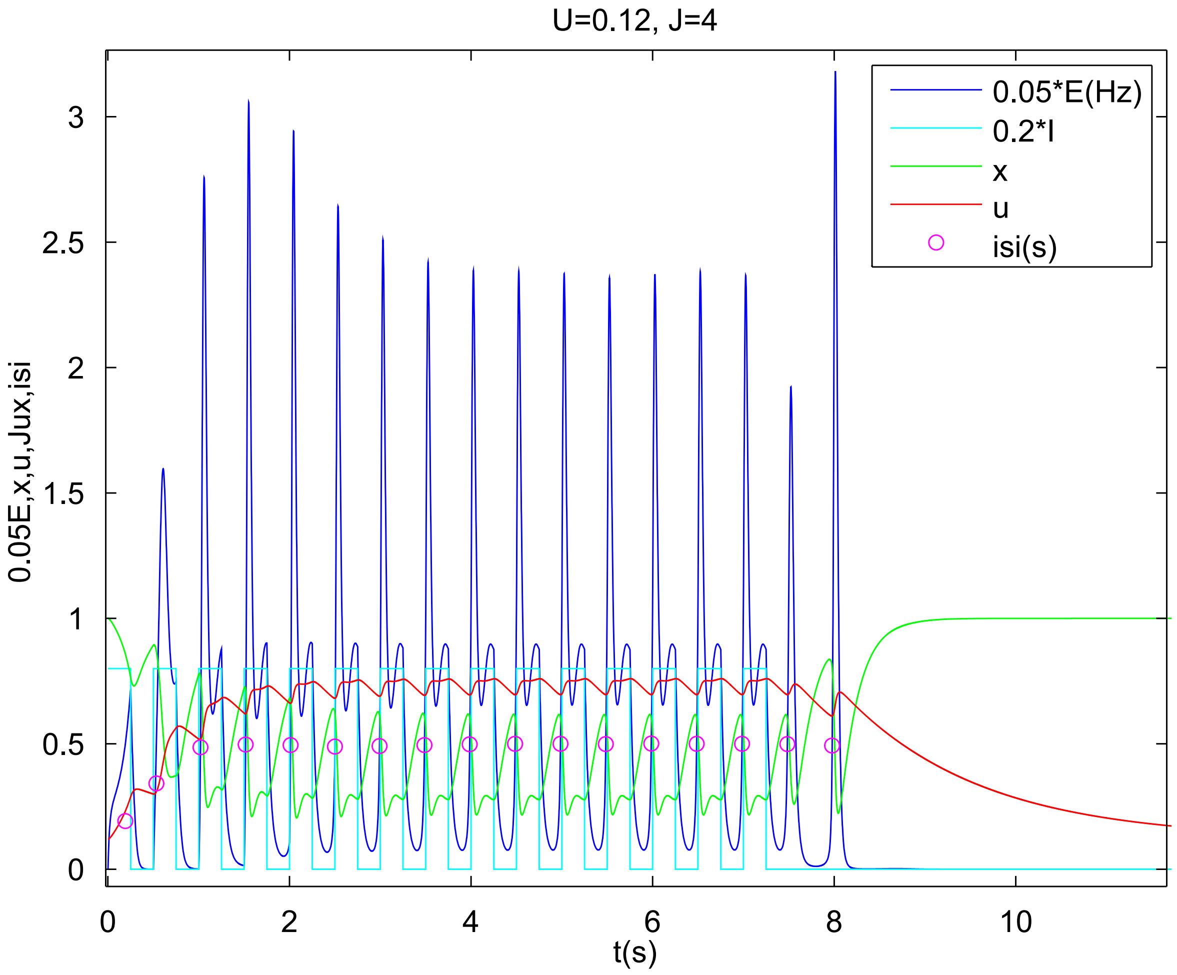
Adaptive of excitability!!!

$\tau = 0.01\text{s}$, $\tau_D = 0.2$ $\tau_F = 1.5\text{s}$

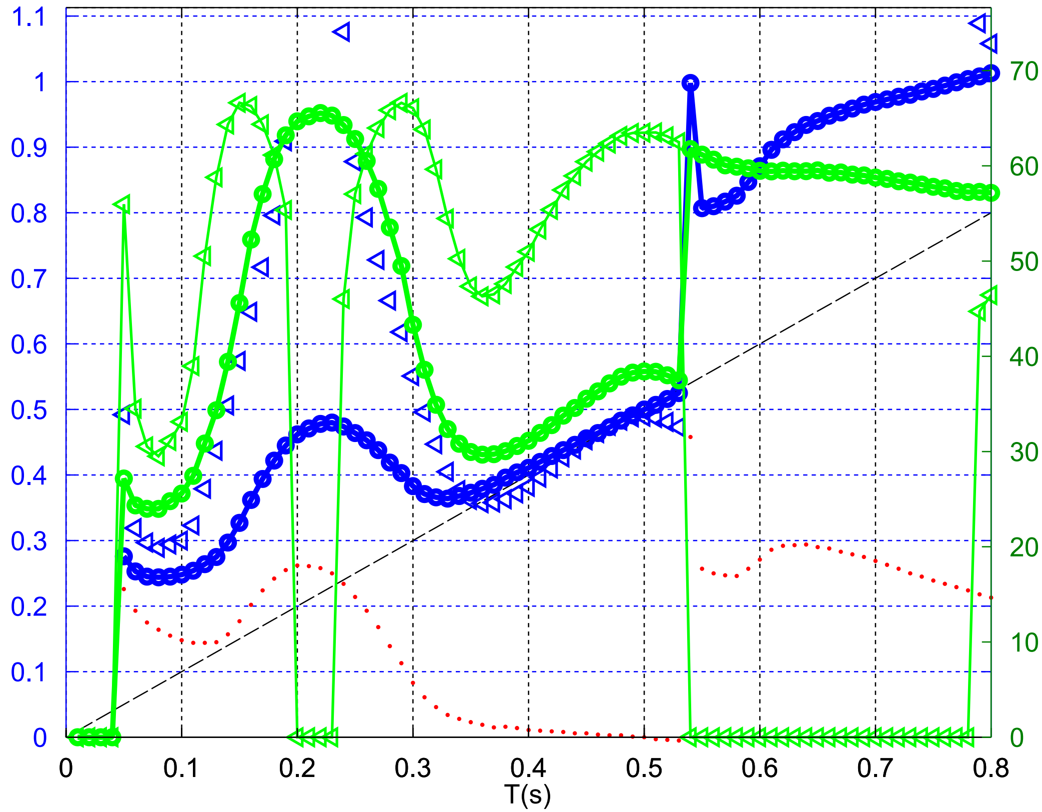


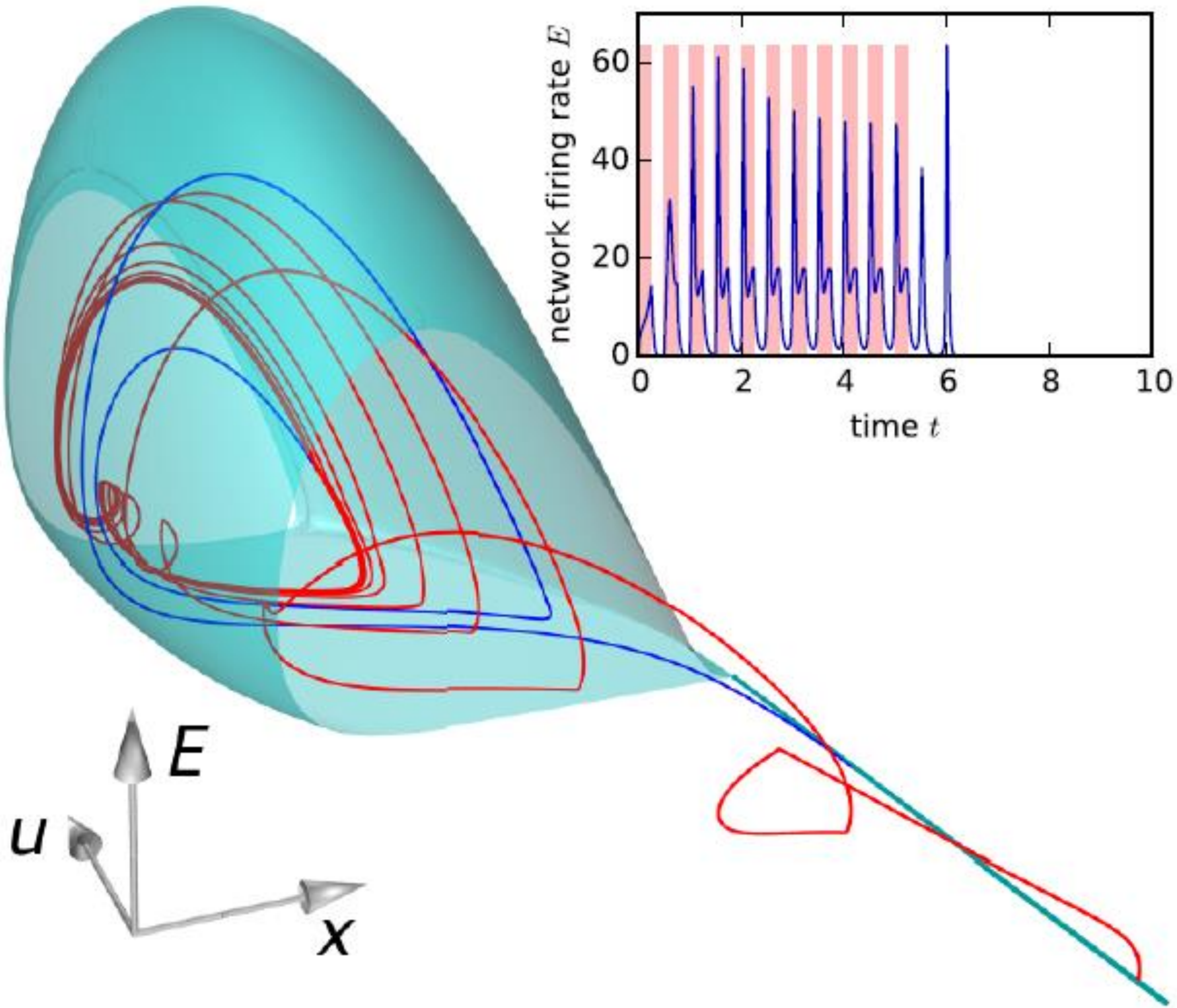
Cortes, J. M., et al. (2013, PNAS 110(41): 16610-16615.

Observation of OSR in TM model



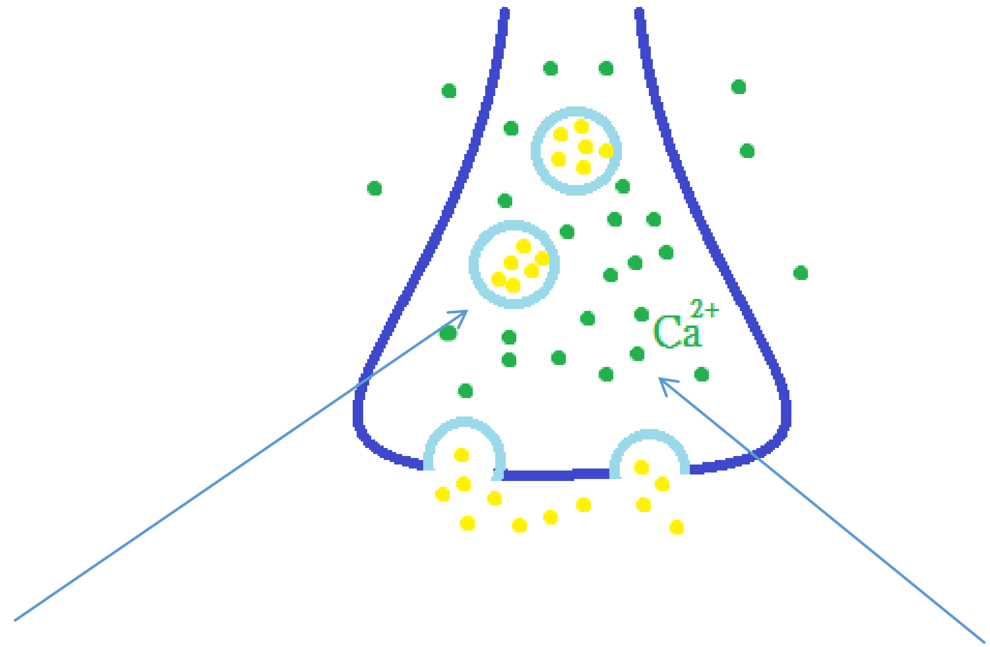
Encoding of stimulation period





network firing rate E
0
20
40
60
0
2
4
6
8
10
time t
E
u
x

Time is coded into Calcium

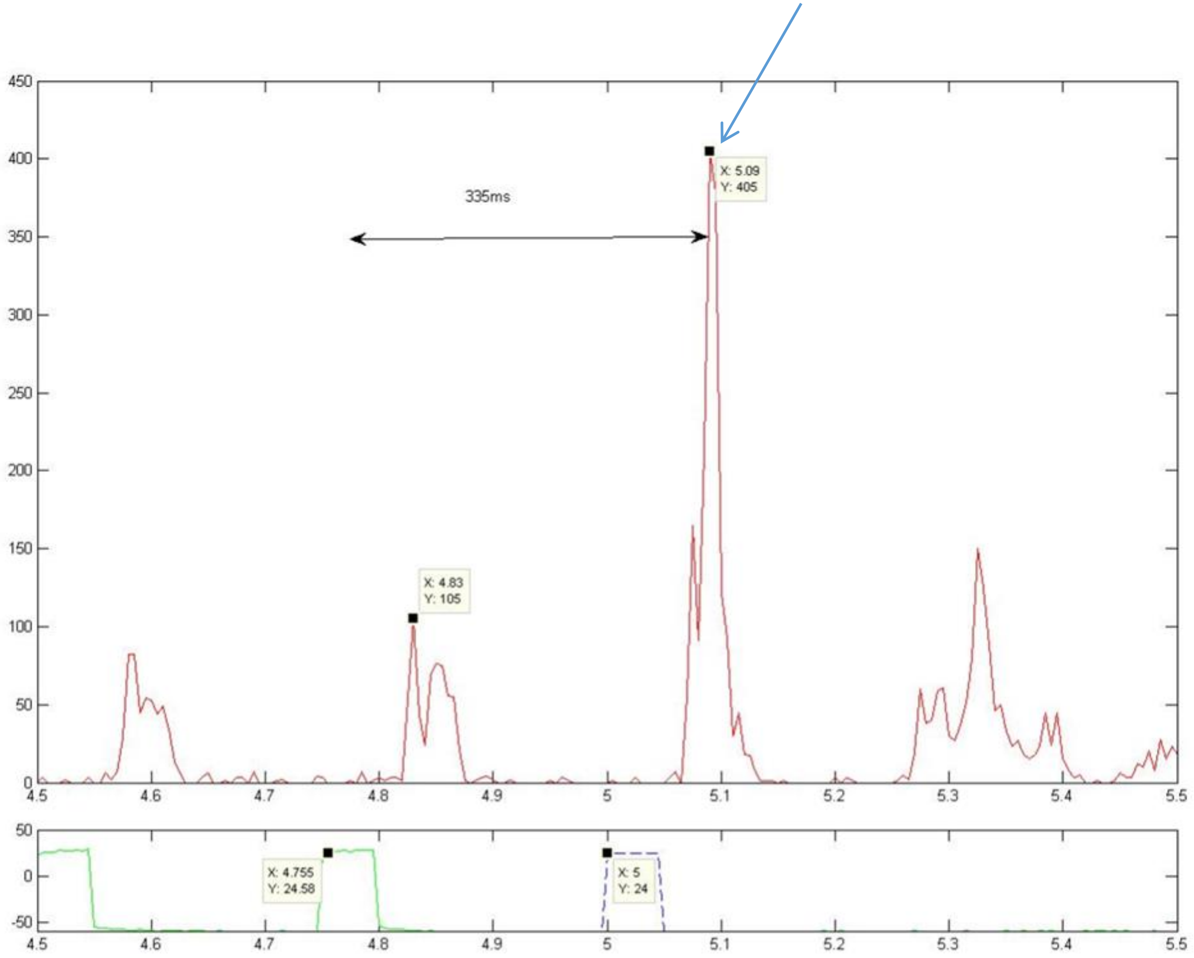


Available neurotransmitter fraction : x

Releasing probability : u
(related to $[Ca^{2+}]$)

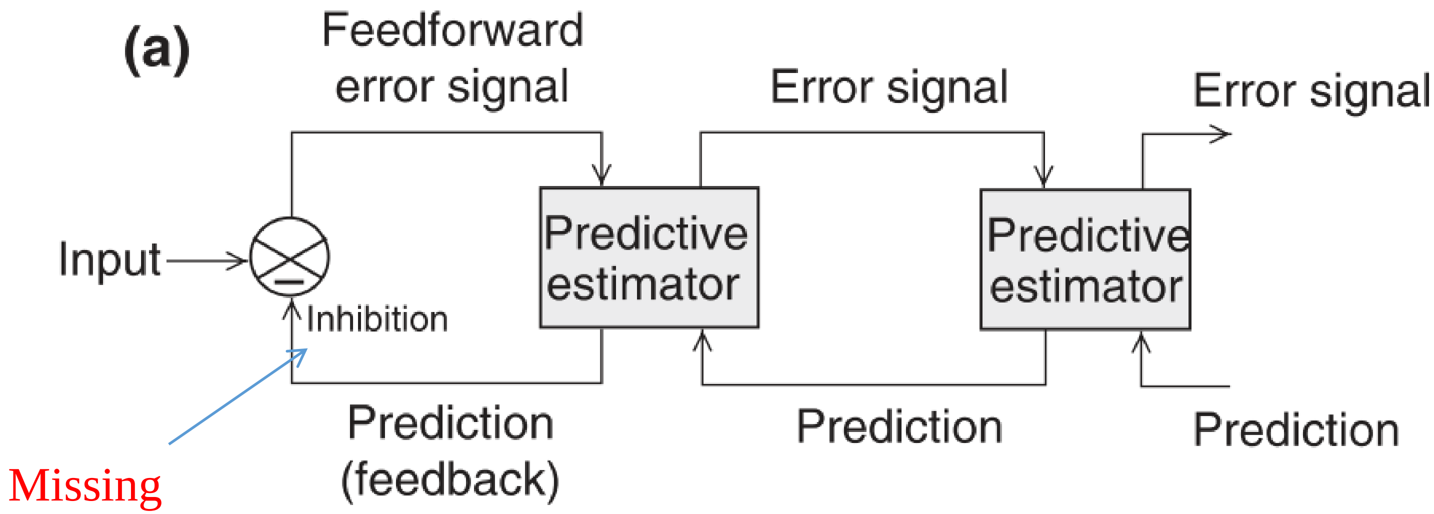
Is adaptation enough?

strongest Response from missing stimulation



Predictive Coding and anticipation

- Minimize flow of information
- Focused only on changes



Rao et al. Wiley Interdisciplinary Reviews-Cognitive Science 2(5): 580-593.

Hallmarks of strong anticipation

- is an achievement by the system as a whole.
- is owed to proper organization.
- uses the natural unfolding of events
- is purely reactive at some level of analysis.
- relates implicitly to future states.

Turvey et al. Cognitive Systems Research 11 (2010) 148–164

How do living systems perceive the external world?

Stimuli	Example of Sensor	Effects
Temperature/Heat	transient receptor potential ion channel	Membrane potential Chemical release
Chemicals	Ca, Na, K channels	Membrane potential Chemical release
Mechanical Stress	mechano-gated potassium channels	Membrane potential Chemical release
Light	Light-gated ion channels Rhodopsin	Membrane potential Chemical release
Time	Adaptive Excitable System (recurrent network + STSP)	Anticipation Sustained reverberations

Conclusions

- Adaptive excitable system is capable of producing anticipative dynamics (OSR)
- Entrained reverberations with short-term synaptic plasticity can sense the periodicity of stimulations with time encoded in [Ca]
- No clock is needed; strong anticipation
- Inhibition needed for predictive coding seen in experiments