COMPUTATIONAL NEUROSCIENCE
Research group at the University of Tartu

A neuronal learning rule for sub-millisecond temporal coding

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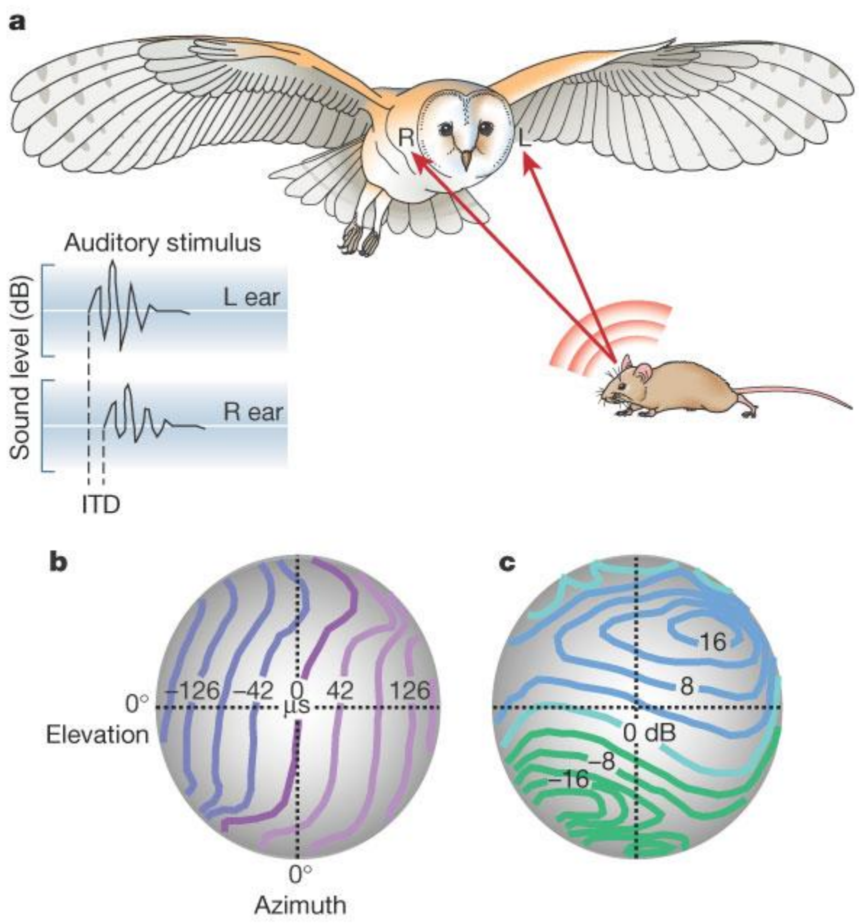


Barn owl (*Tyto alba*) locates prey with precision of 1-2 degrees

that requires time precision of less than 5 μs.

How?

Phase locking

http://auditoryneuroscience.com/ear/phase_locking

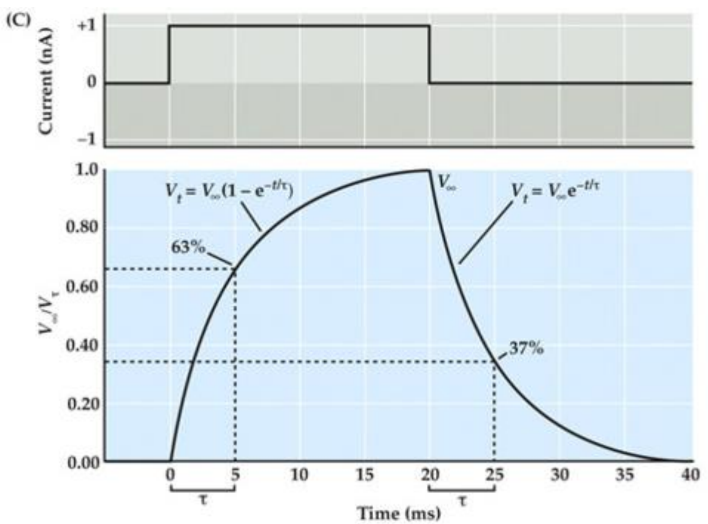
Time-coding

Very precise

Synaptic input current τ_s

Membrane time constant $\tau_m = r_m c_m$

e.g. width of single **excitatory postsynaptic potential** at half maximum (63%) amplitude



Time-coding

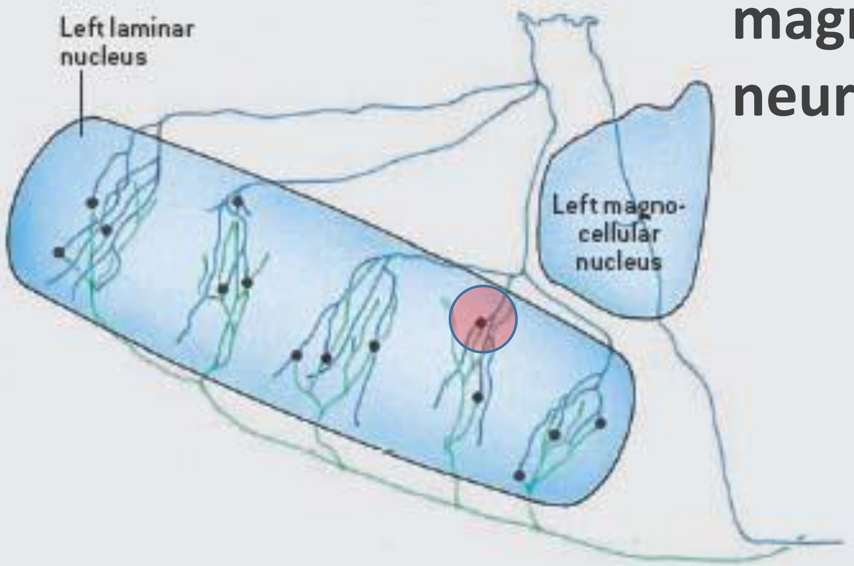
Synaptic input current $\boldsymbol{\tau_s}$ **= 200 µs**
Membrane time constant $\boldsymbol{\tau_m}$ **= 2 ms**

PARADOX

Neurons are 10x slower than behavioral sensitivity to time differences

Can neuronal firing be more precise than the neuronal processes involved?

Model: ‘integrate-and-fire’ neuron

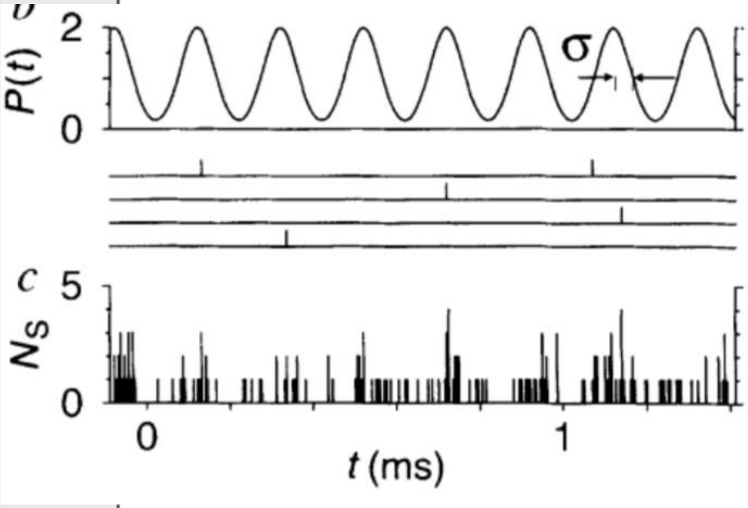


Input from 154 presynaptic magnocellular neurons

Fibers from the magnocellular nucleus serve as delay lines, and neurons in the laminar nucleus act as coincidence detectors in the owl's brain. When impulses traveling through the left (*blue*) and right (*green*) fibers reach laminar neurons (*black dots*) simultaneously, the neurons fire strongly.

Single frequency pure tone e.g. 5kHz, T=200us

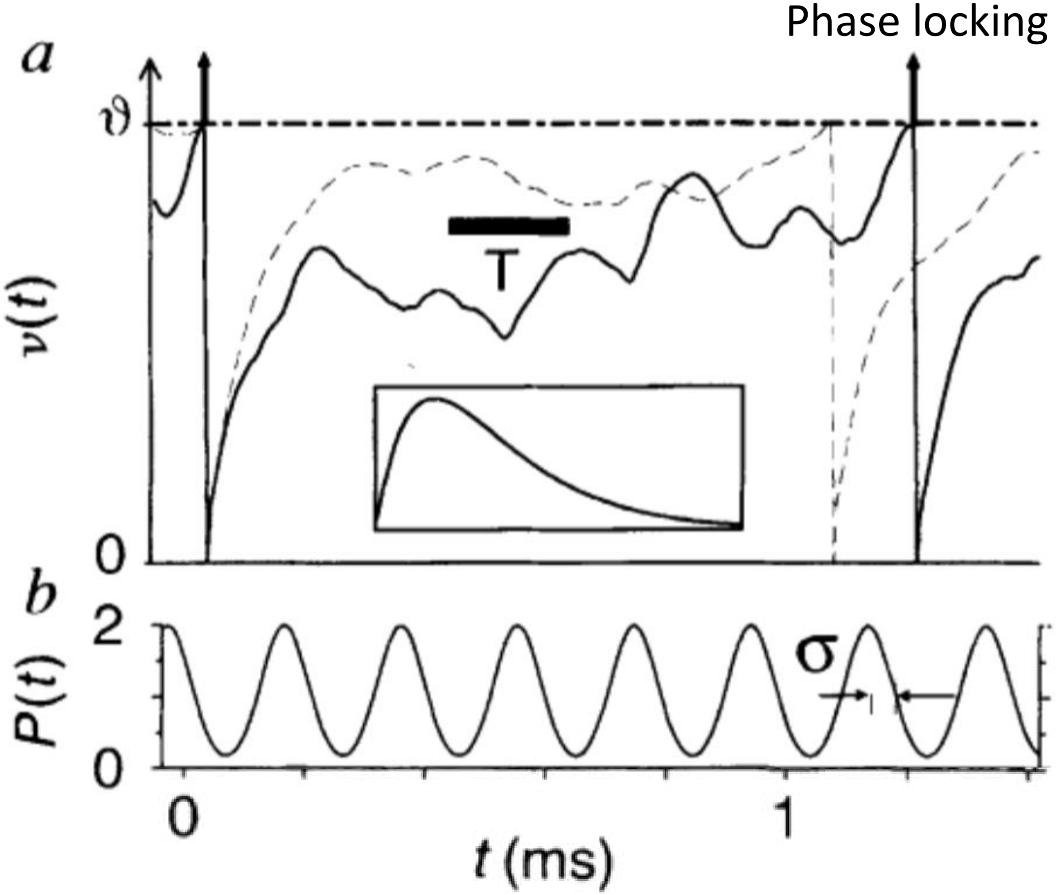
Input as sequence of spikes



Specific mean phase of tone

40 us ‘jitter’ as noise

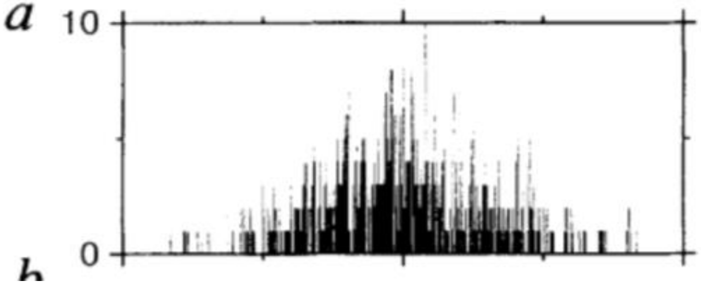
Accurate phase locking



Input with a **coherent common mean phase** leads to oscillating membrane potential

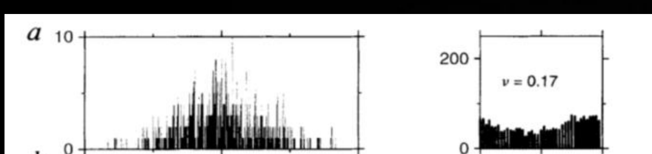
Random phase input leads to aperiodic fluctuations,

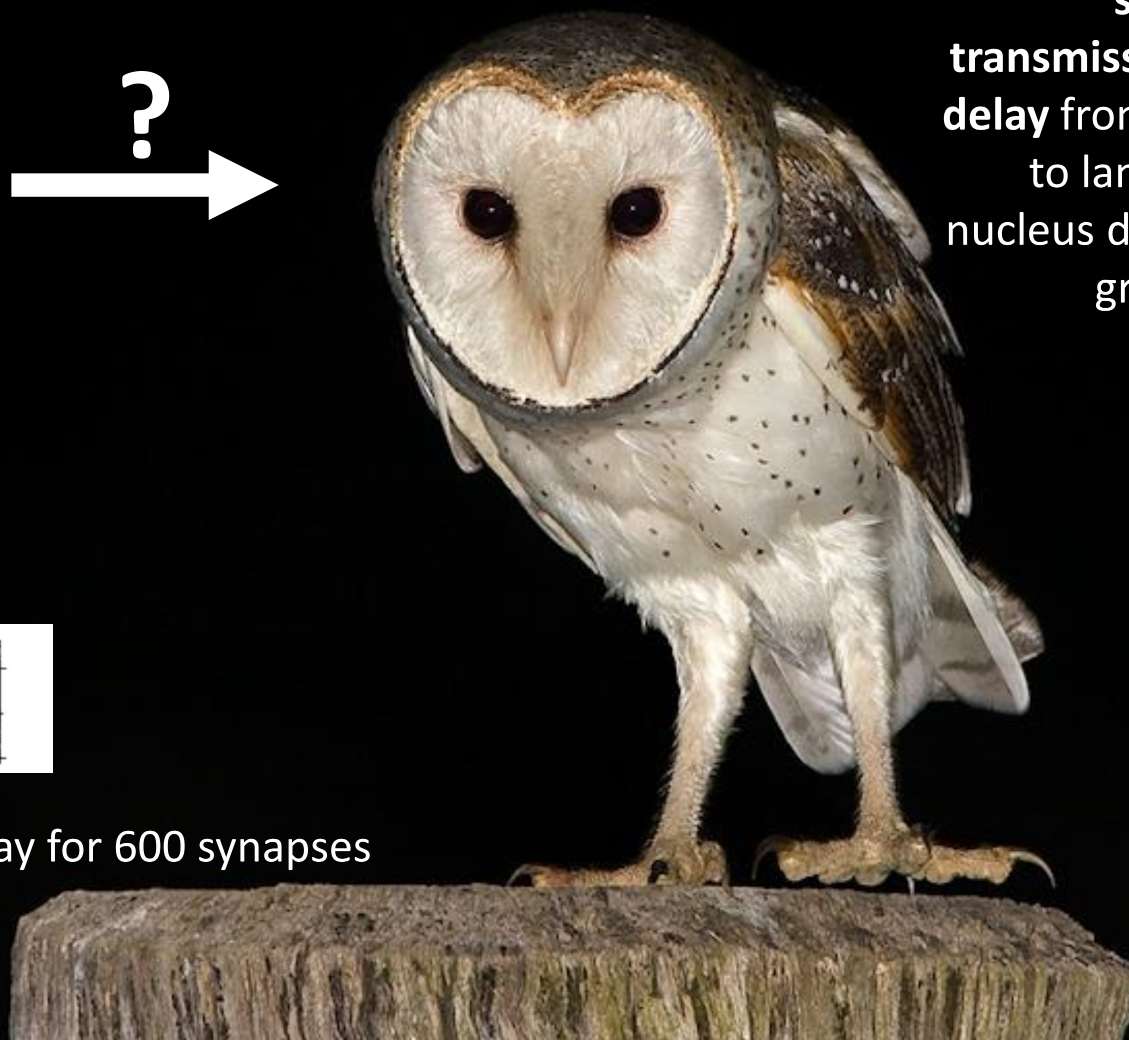
i.e. the output spikes have uniform distribution:



For adults **signal transmissioon delay** from ear to laminar nucleus differs greatly

?

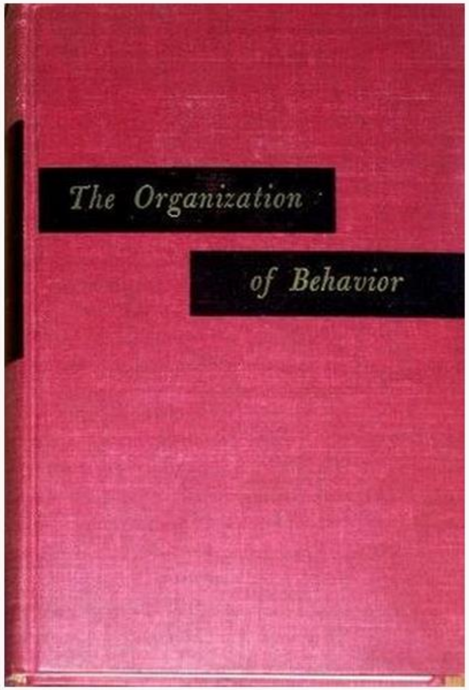




Left: Signal transmissioon delay for 600 synapses
Right: Output phases

Hebbian learning rule

The Organization of Behavior



Author Donald O. Hebb

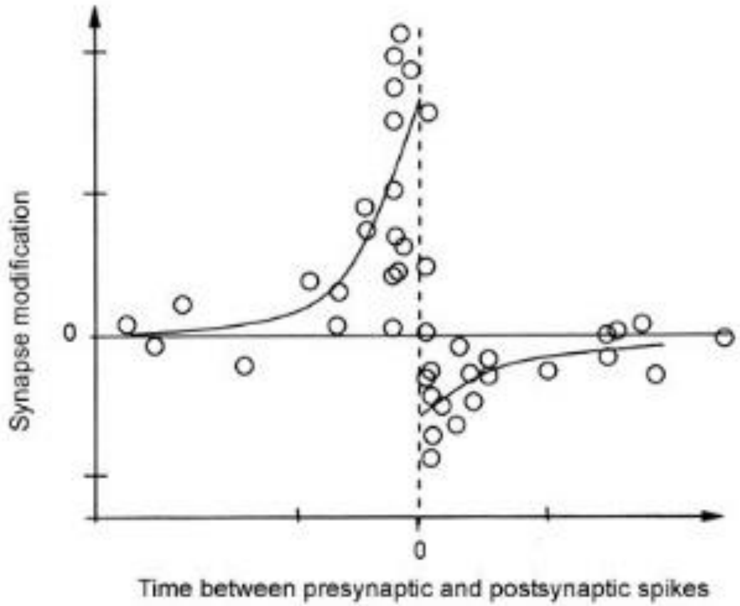
'Cells that fire together, wire together'

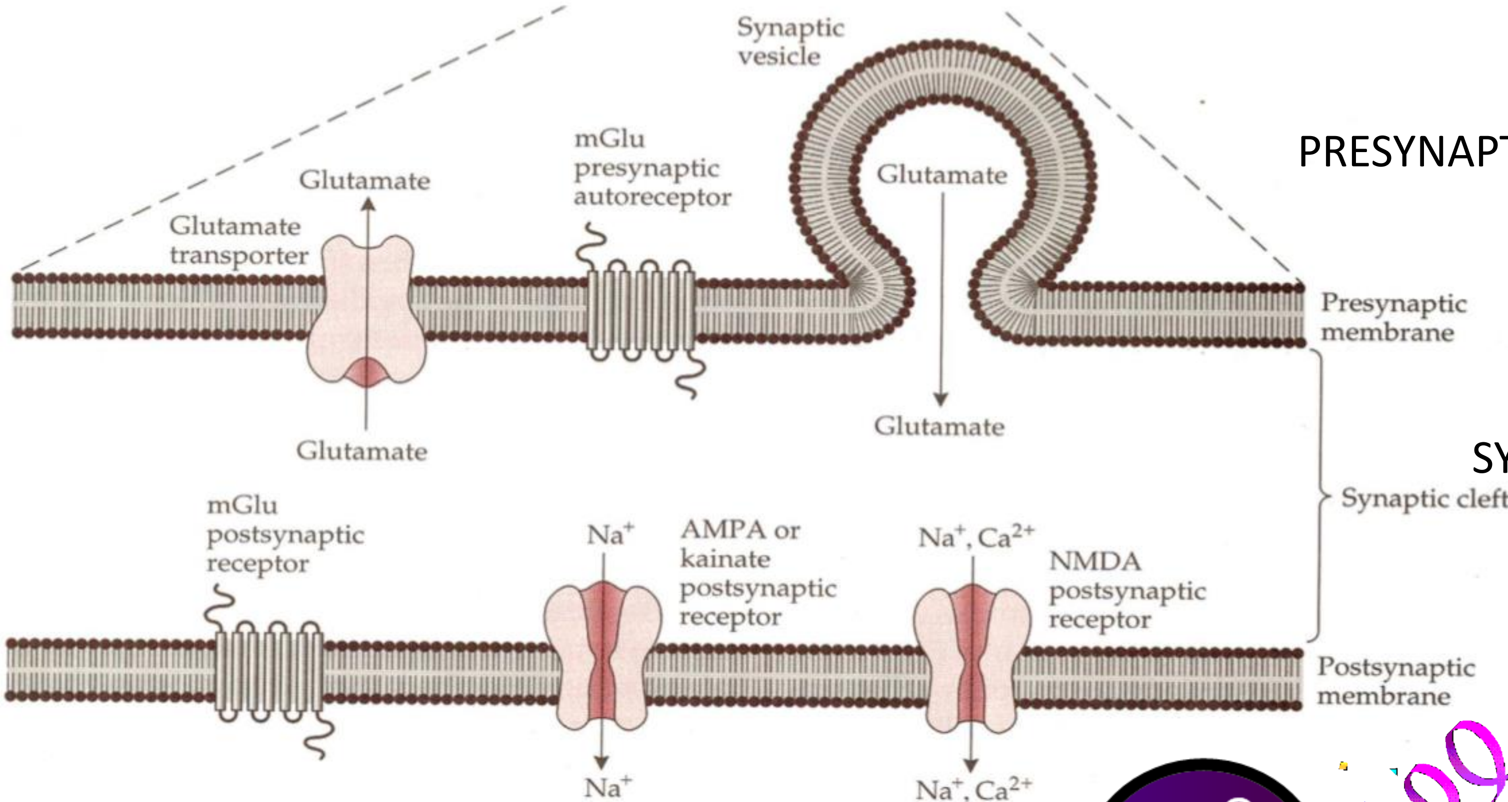
In reality 'just before'

Adaptation during learning

Spike-timing-dependent plasticity (STDP)

Important synapses are strenghtened, *vice versa*



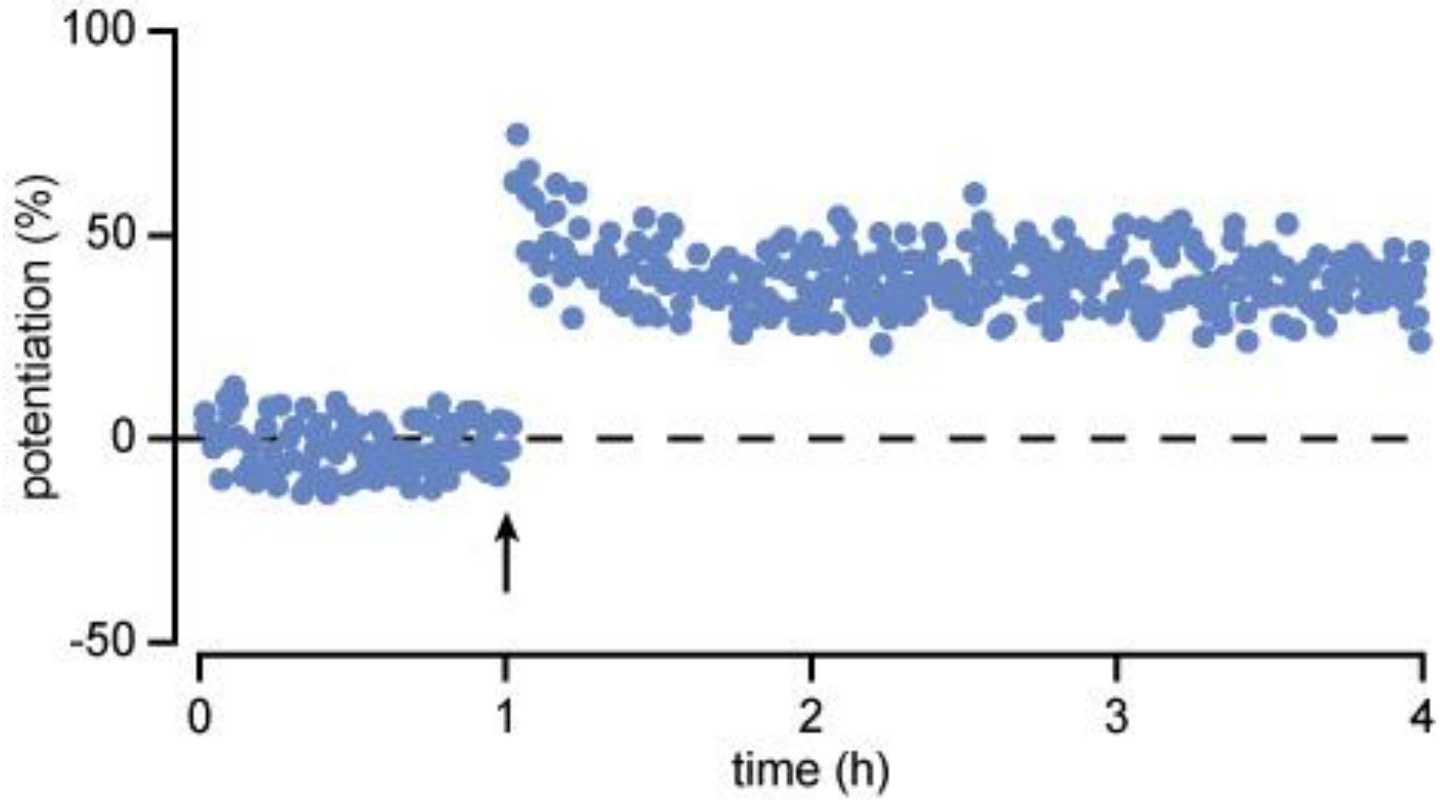


PRESYNAPTIC AXON

SYNAPTIC CLEFT

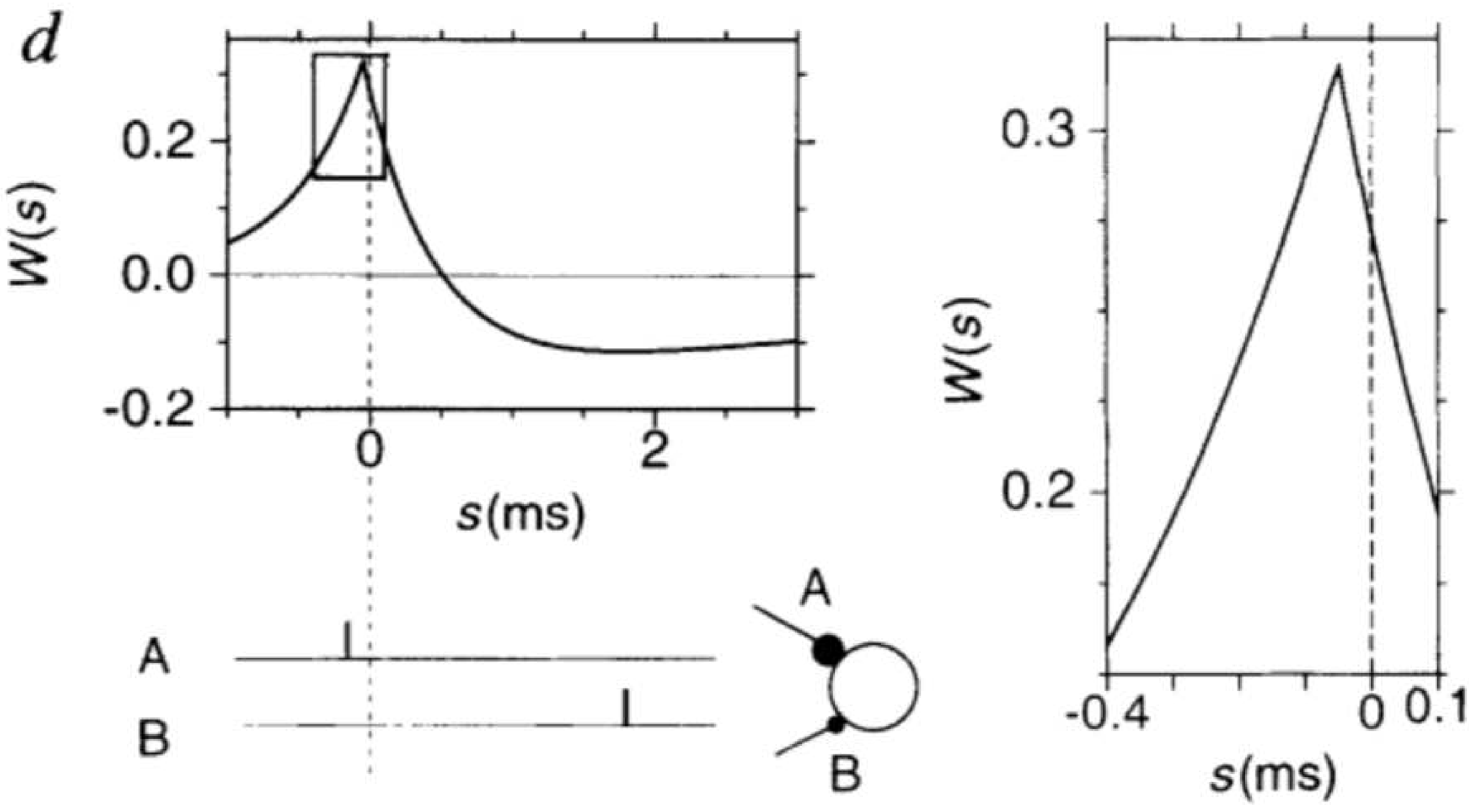
POSTSYNAPTIC DENDRITE

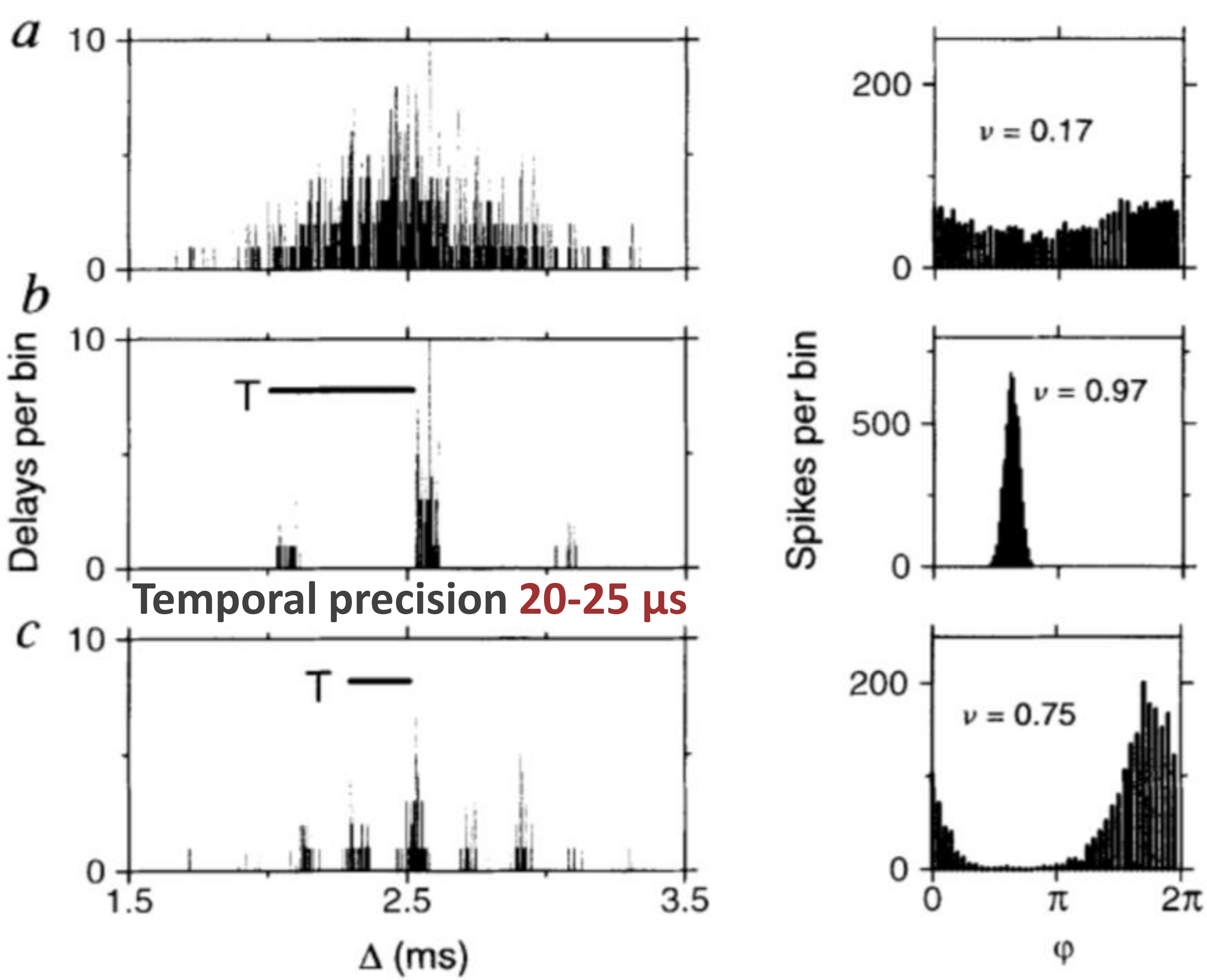
Long-term potentiation



Learning interval W(s)

s – difference between presynaptic input and postsynaptic firing





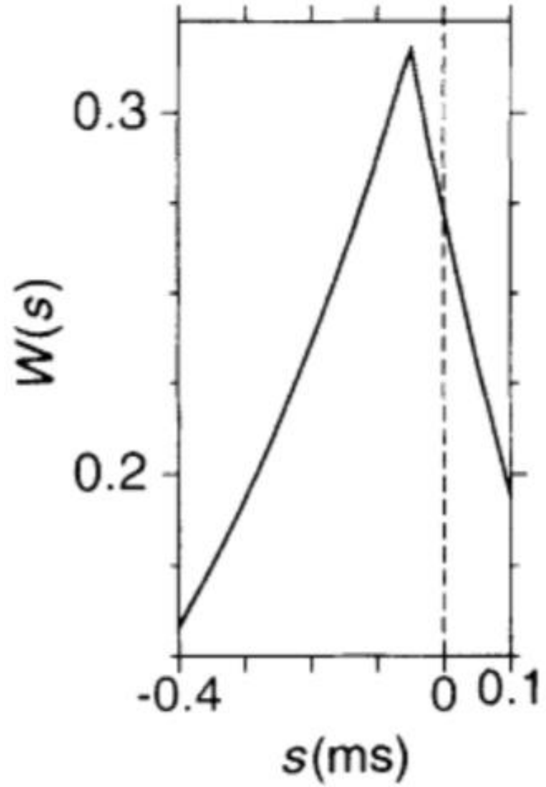
Structured distribution

Delay period T

Not tuned previously

Different between inputs

Efficacy does not depend on W(s)

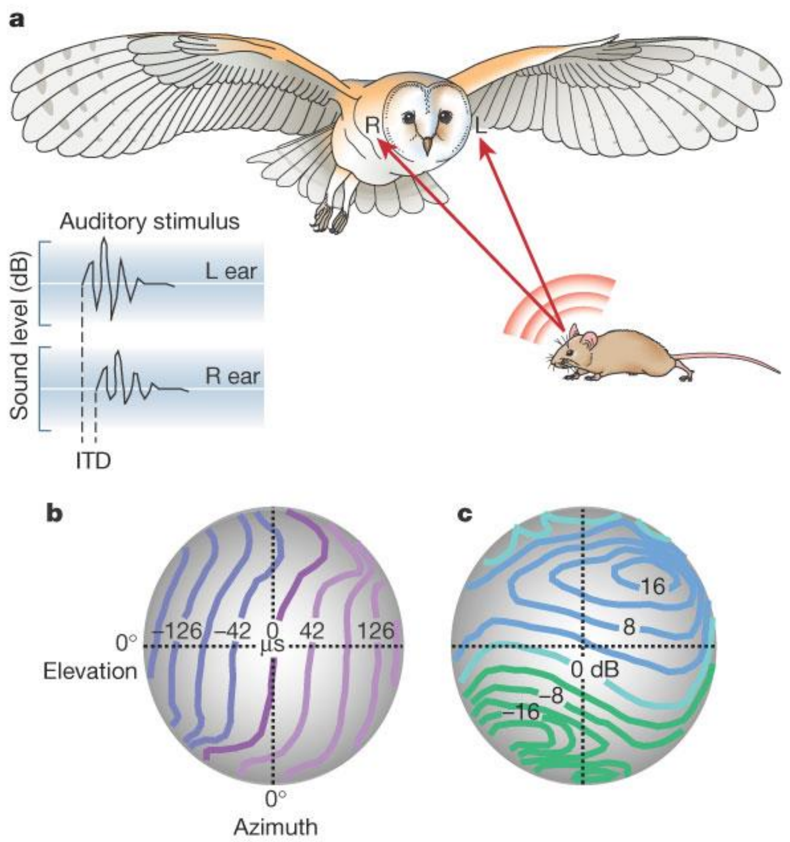


$$\max\big(W(s)\big) = W(-\tau_s/2)$$

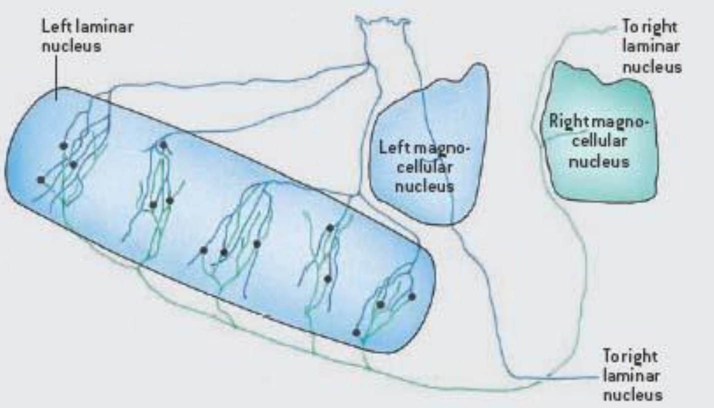
where τ_s is rise time of p.s.p.

I.e. coherently arriving input trigger p.s. spike with mean delay of $\tau_s/2$

Interaural time difference (ITD)



Input from two ears



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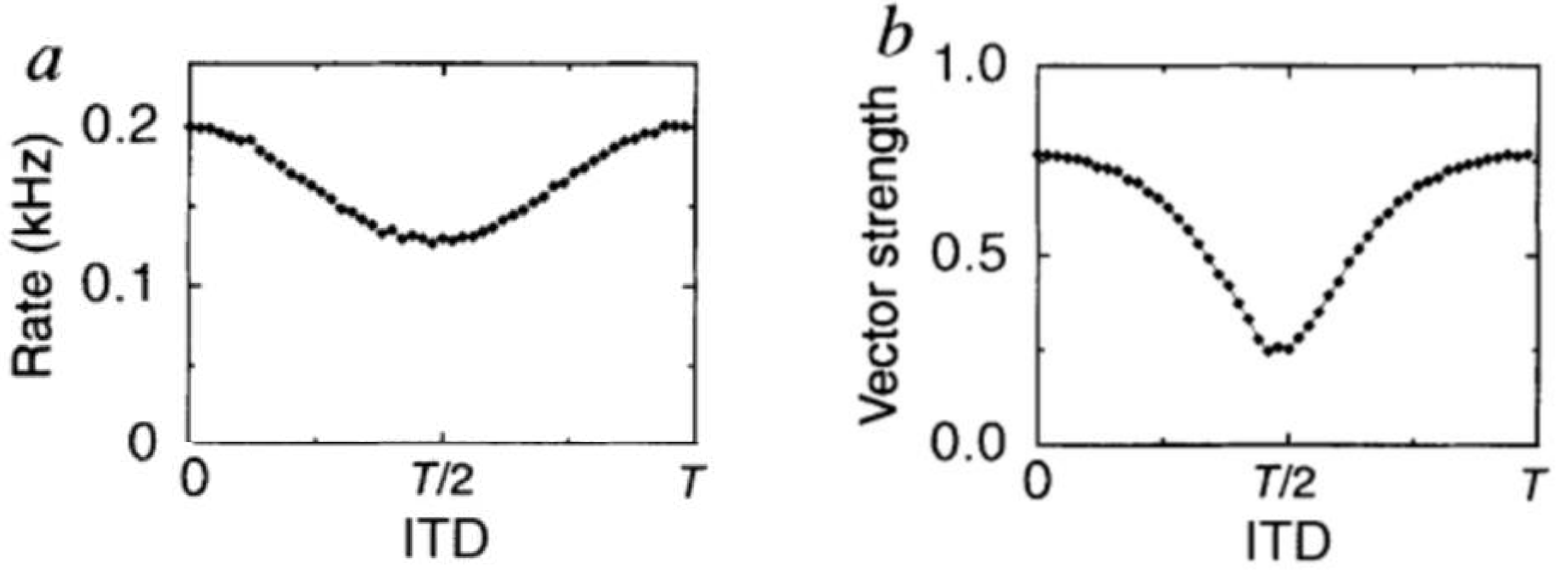
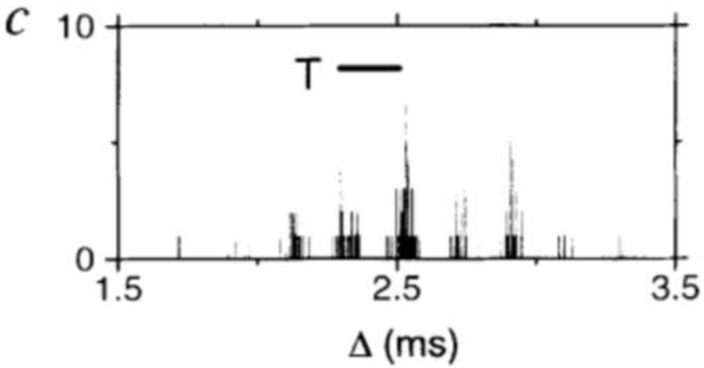
ITD tuning curve

During learning, both ears are stimulated by the same signal and fixed ITD

If ITD does not match, phase locking breaks



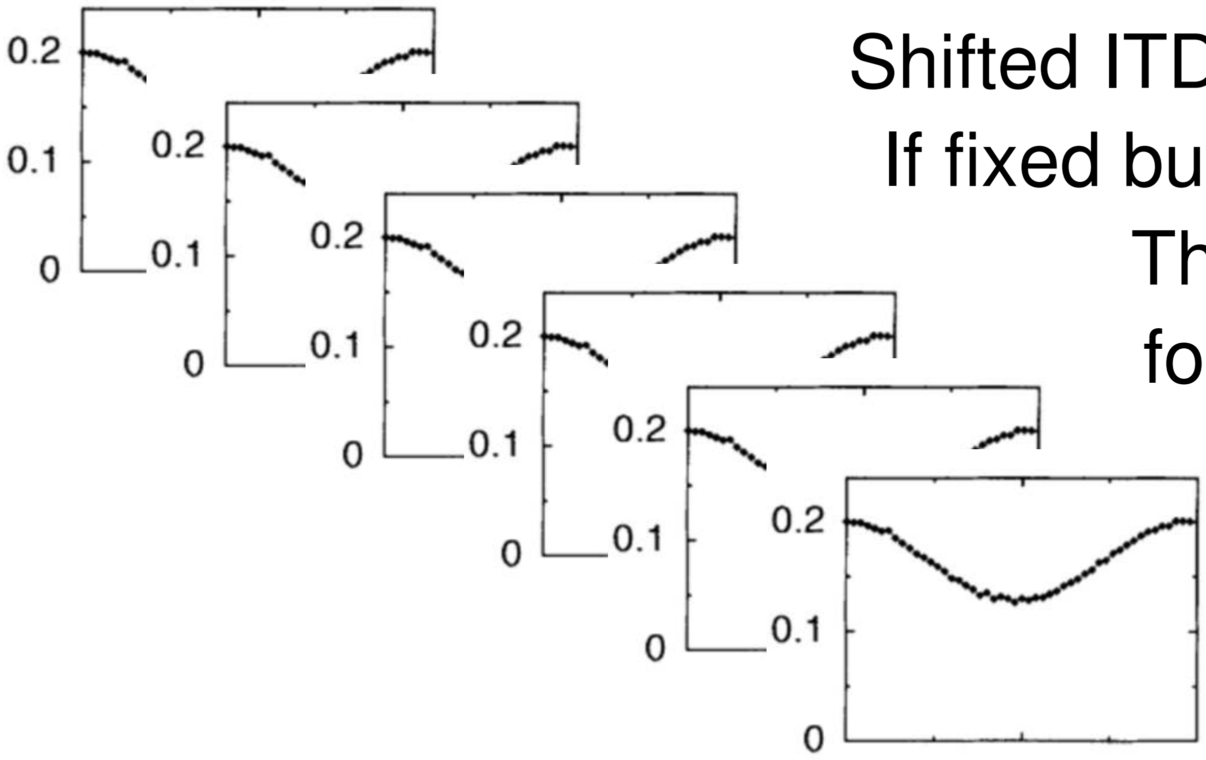
Single laminar neuron
precision is limited to 20-25 μs



Barn owl temporal resolution
5 μs

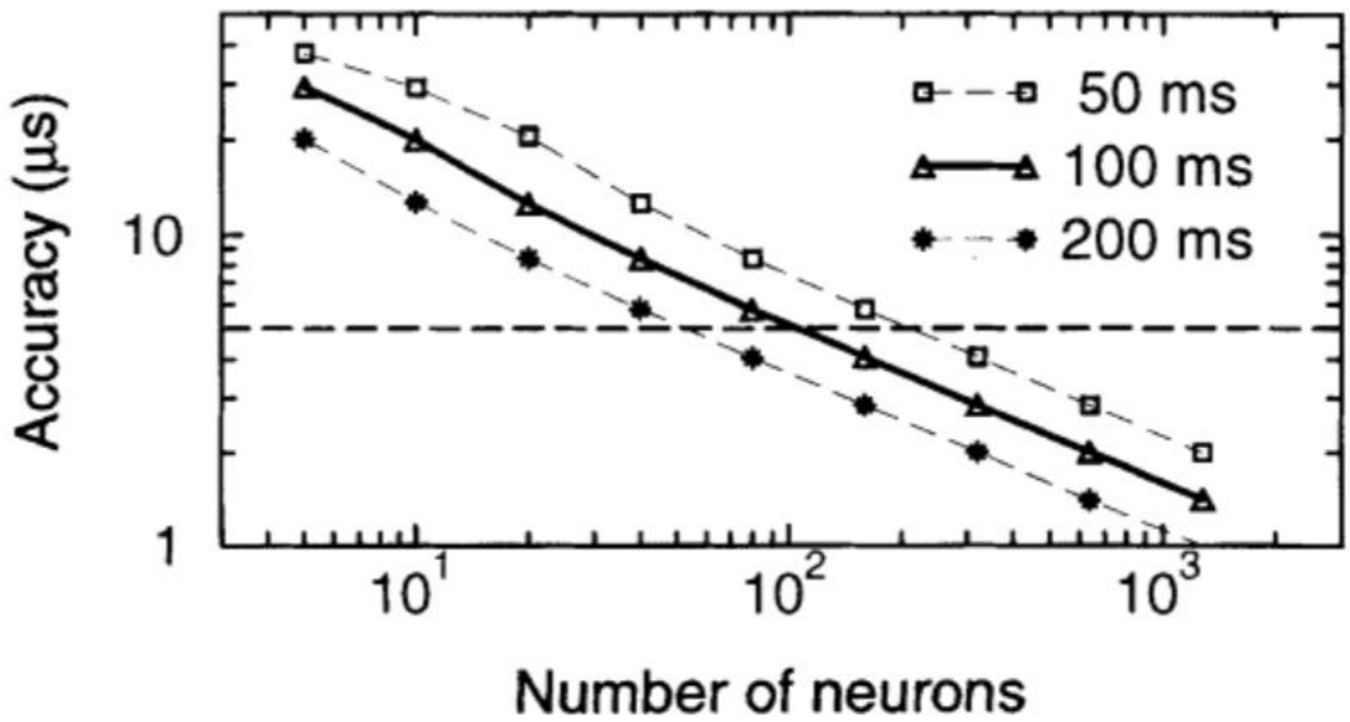
Ahaa! Reaction time 100 ms

Group of laminar neurons

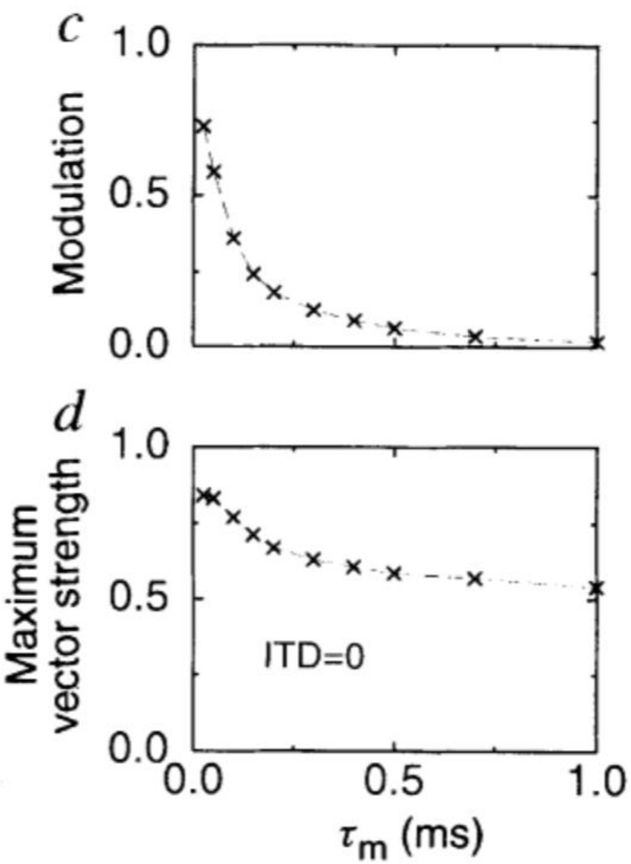


Shifted ITD tuning curves
If fixed but unknown ITD
Then get optimal
for each neuron,
weighted by
N of spikes
per 100ms

Population coding



Membrane time constant



ITD tuning breaks down rapidly if τ_m exceeds 0.1 ms

Where modulation is $(fmax - fmin)/fmax$

Temporal precision depends only weakly on τ_m

What does this tell us? (laconically)

Coherent input → spike timing precision << τ_m

Hebbian learning rule works

Works for two ears

Allows generalization: τ_m 10-20 ms, accuracy 1-3 ms

Reading

Gerstner, W., Kempter, R., van Hemmen, J. L., & Wagner, H. (1996). *Nature*, *383*, 76-78

Carr, C. E. (1993). *Annual review of neuroscience*, *16*(1), 223-243