How the brain maintains information in mind

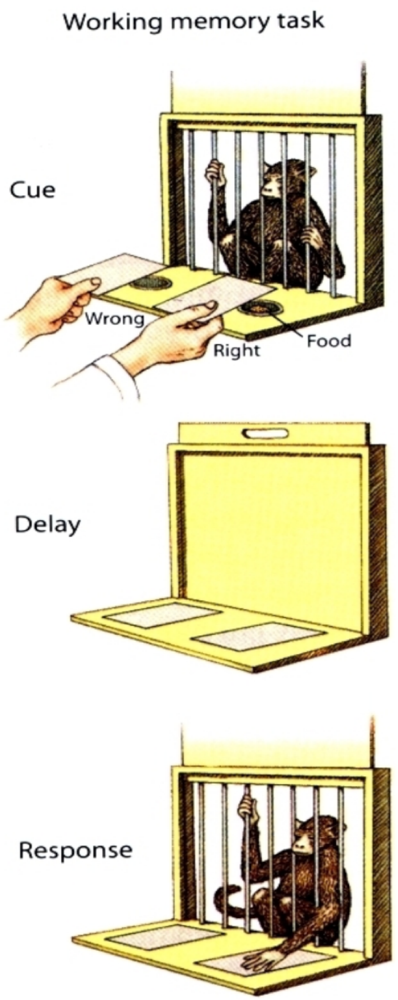
Seán Froudist-Walsh

Lecturer in Computational Neuroscience

Learning objectives

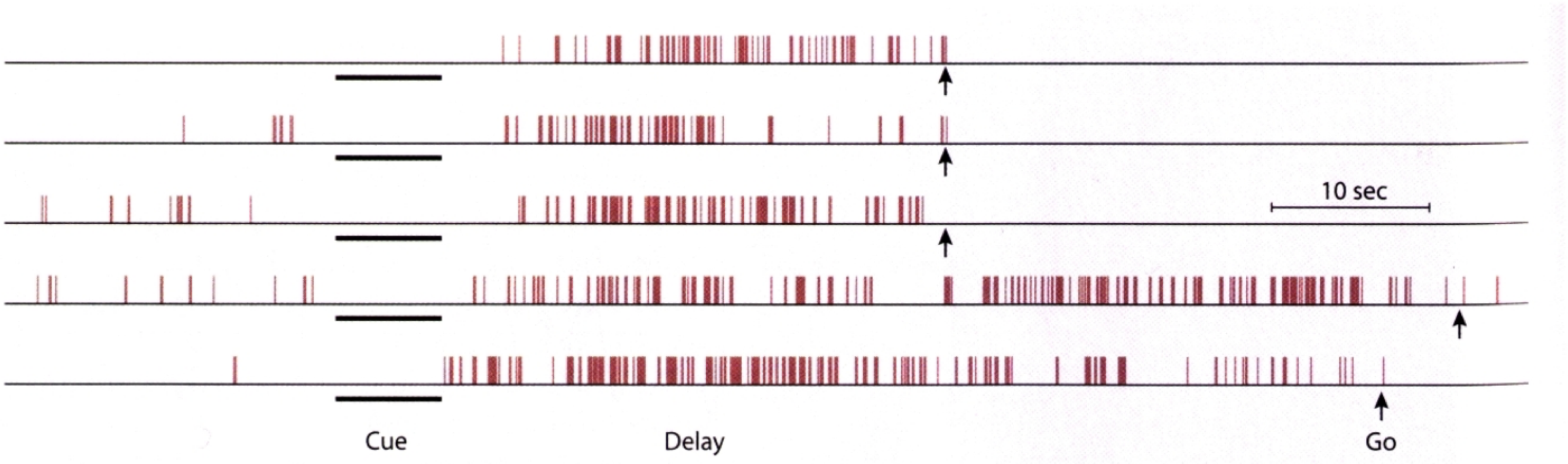
- To understand the neural activity that produces working memory
- To understand the concept of bifurcations in nonlinear dynamical systems
- To learn a neural network model of working memory

Working memory in the laboratory



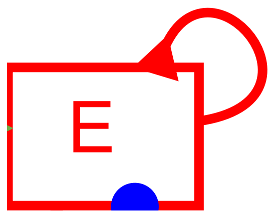
Goldman-Rakic, 1992
Wisconsin General Task Apparatus (WGTA)

Persistent activity supports working memory (probably)

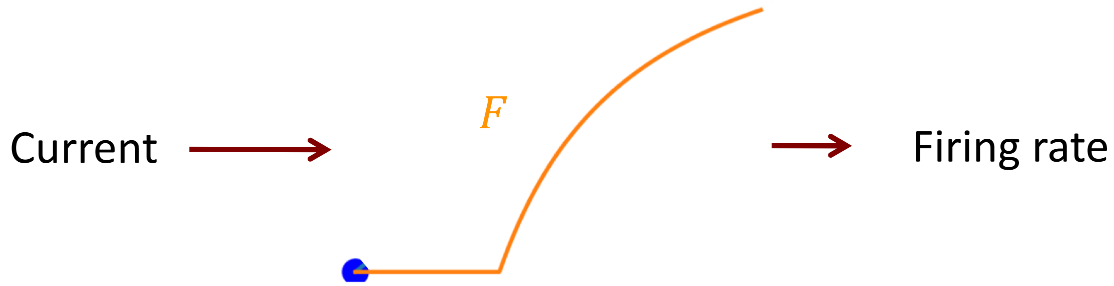


Fuster & Alexander, 1971

A simple firing rate model



A population of excitatory neurons



$$\tau \frac{dr_E}{dt} = -r_E + F\left(J_{E,E}\, r_E + I_{ext}\right)$$

At each step in time the firing rate of the Excitatory neurons would drop down towards zero if not for synaptic and external inputs.

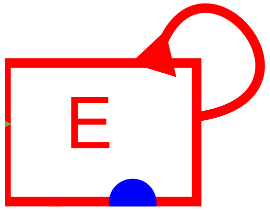
Activity is pushed up by

- positive connections from the Excitatory population to itself
- and external input

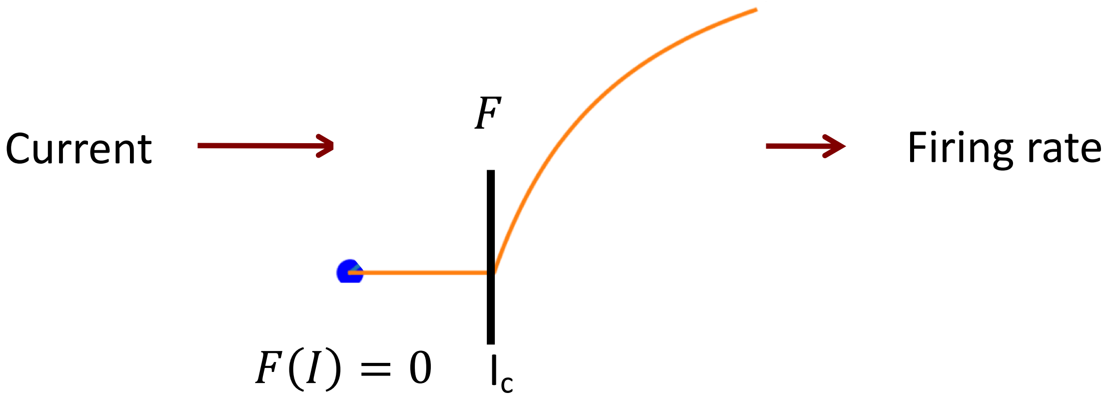
The size of the response to input depends on the neuronal input-output function.

The time constant determines how quickly the rate changes in response to input

A simple firing rate model



A population of excitatory neurons

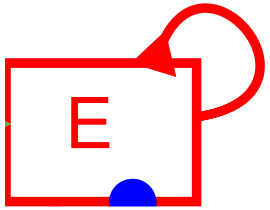


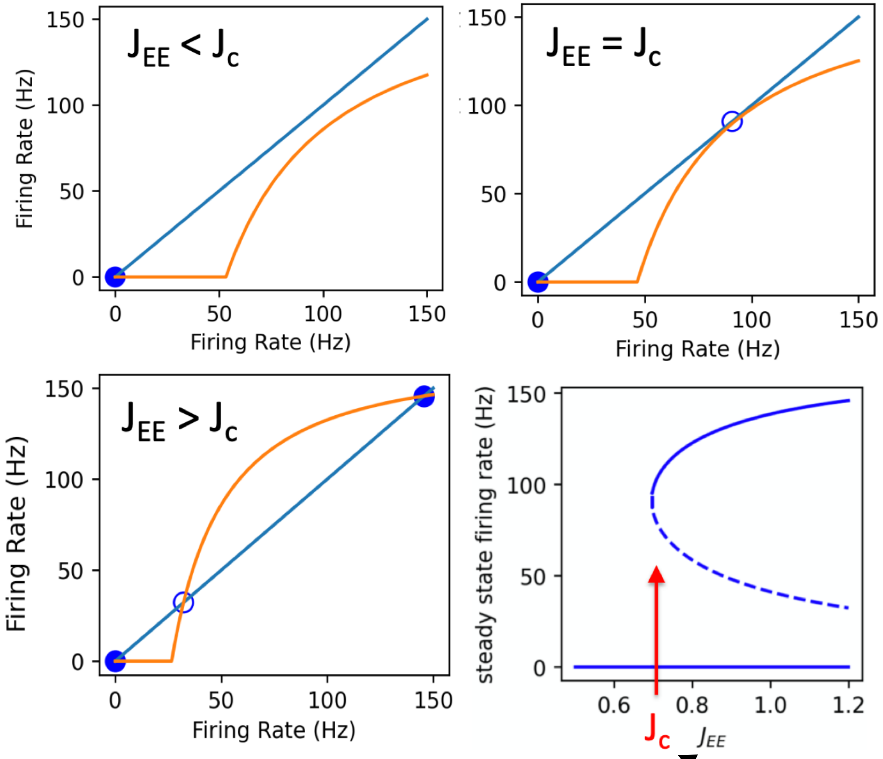
$$F(J_{E,E} r_E + I_{ext}) = 0 \text{ for } (J_{E,E} r_E + I_{ext}) < I_c$$

$$r_E < (I_c - I_{ext}) / J_{E,E}$$

$$\tau \frac{d}{dt} r_E = -r_E + F(J_{E,E}\, r_E + I_{ext})$$

What are the self-sustained steady states with $I_{ext} = 0$?





Bifurcation diagram

Bifurcation point

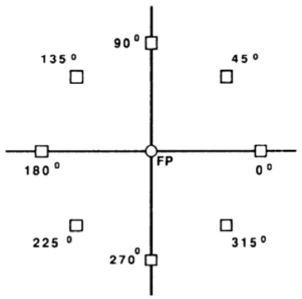
Fig: Xiao-Jing Wang

$$\tau \frac{d}{dt} r_E = -r_E + F\,(J_{E,E}\; r_E\;)$$

$$\frac{d}{dt} r_E = 0$$

$$r_E = F\,(J_{E,E}\; r_E\;)$$

Stimulus-specific persistent activity



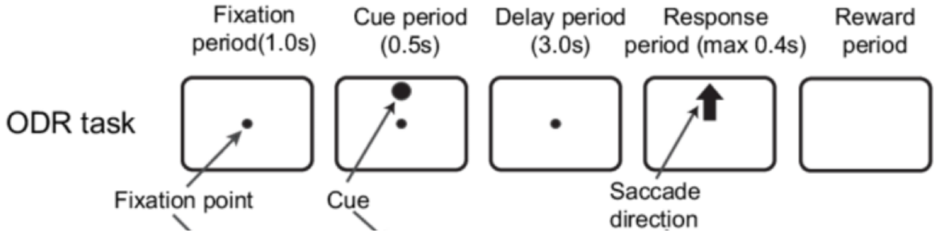


image: Shintaro Funahashi

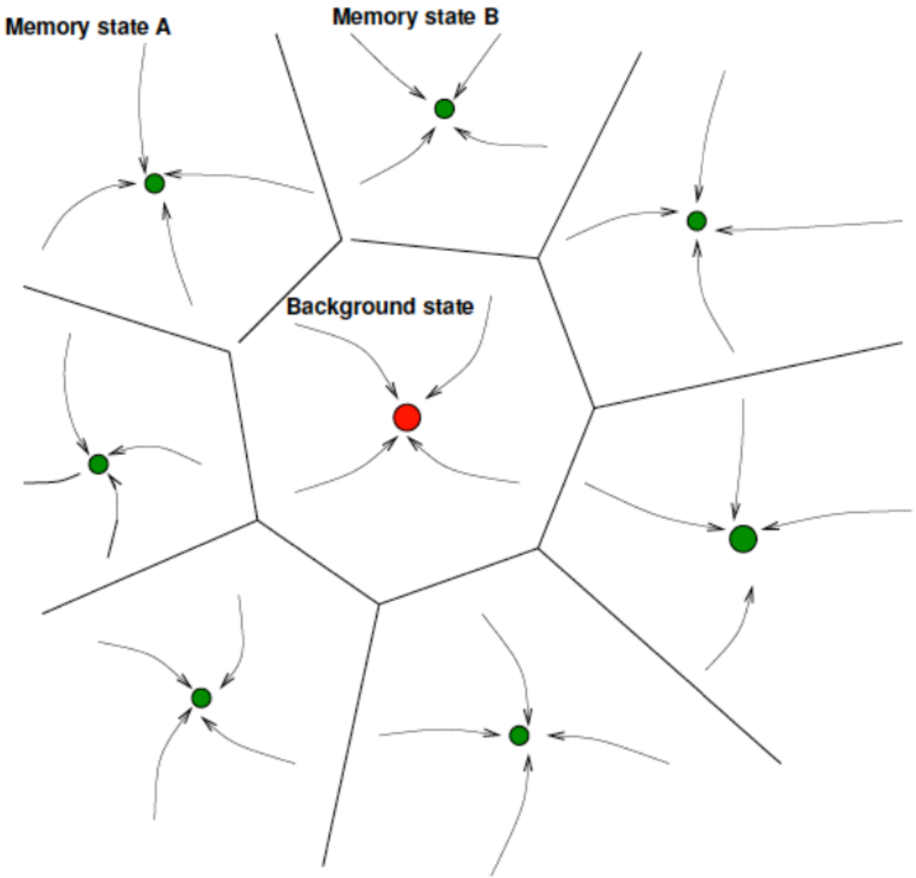
Occulomotor delayed response (ODR) task

Funahashi, Bruce & Goldman-Rakic, 1989

Stimulus-specific persistent activity (definition)

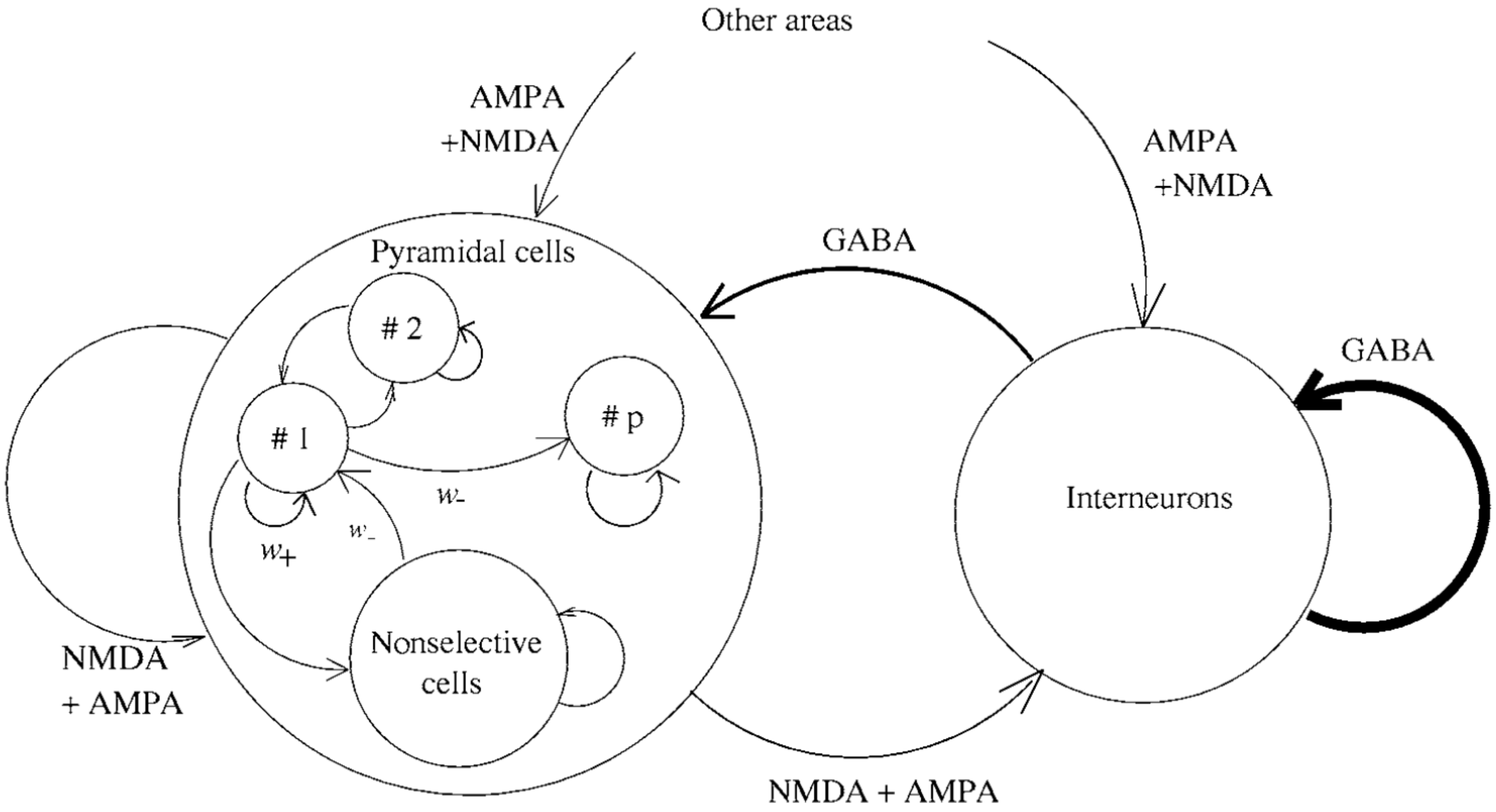
- *Stimulus-specific persistent activity* is
  - self-sustained activity
  - that is maintained at a higher than baseline level during the delay period of a working memory task (i.e. in the absence of a stimulus)
  - that is higher for the preferred stimulus than other stimuli

Basins of attraction



Brunel (2005)

A spiking neural network model of working memory in prefrontal cortex



Brunel & Wang, 2001

Recap from earlier lectures

Neurons

Linear integrate and fire

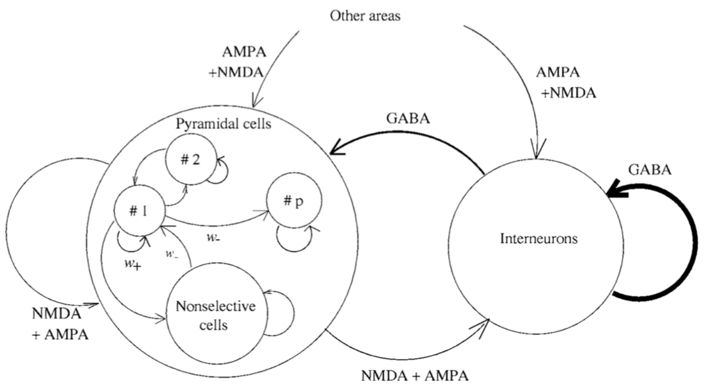
$$\tau_m \frac{dV}{dt} = E_L - V + R_m \boxed{I}$$

Synapses

Excitatory neurons release glutamate
This is received by two major types of receptors
Slow NMDA receptors (τ = 60-100ms) and fast AMPA receptors (τ = 2 ms)
This causes an increase in the voltage in the postsynaptic cell and makes it more likely to spike

Inhibitory neurons release GABA
This is received by $GABA_A$ receptors (τ = 5 ms)
This causes an decrease in the voltage in the postsynaptic cell and makes it less likely to spike

A spiking neural network model of working memory in prefrontal cortex



Change in membrane potential for excitatory neurons

$$C_m \frac{d\, V_i^E}{dt} = -\sum_{j=1}^{N_E} w_{ij}^{EE}\left(G_{E,E,AMPA} s_j^{AMPA} + G_{E,E,NMDA} f(V_i^E) s_j^{NMDA}\right)(V_i^E - V_E)$$
$$-\sum_{j=1}^{N_I} G_{E,I} w_{ik}^{EI} s_k^I (V_i^E - V_E) \quad - G_L(V_i^E - V_L) \quad + I_{ext,i}^E(\mathrm{t})$$

At each step in time
the membrane potential of each neuron
changes in proportion to
the amount of electrical charge that can be stored at the membrane
according to
the synaptic inputs from excitatory cells
the synaptic inputs from inhibitory cells
the leak current
and the external input

$$f(V) = \frac{g_{\mathrm{NMDA}}\,(V(t) - V_{\mathrm{E}})}{(1 + [\mathrm{Mg}^{2+}]\exp(-0.062V(t))/3.57)}$$

$$C_m \frac{dV_i^I}{dt} = -\sum_{j=1}^{N_E} w_{ij}^{IE}(G_{IE,AMPA} s_j^{AMPA} + G_{IE,NMDA} f(V_i^I) s_j^{NMDA})(V_i^I - V_E)$$
$$-\sum_{k=1}^{N_I} G_{II} w_{ik}^{II} s_k^I (V_i^I - V_I) - G_L(V_i^I - V_L) + I_{ext,i}^I(t)$$

Brunel & Wang, 2001

Synaptic dynamics

AMPA (fast excitation):

$$\frac{ds_j^{\mathrm{AMPA}}(t)}{dt} = -\frac{s_j^{\mathrm{AMPA}}(t)}{\tau_{\mathrm{AMPA}}} + \sum_k \delta\left(t - t_j^k\right)$$

GABA (inhibition):

$$\frac{ds_j^{\mathrm{GABA}}(t)}{dt} = -\frac{s_j^{\mathrm{GABA}}(t)}{\tau_{\mathrm{GABA}}} + \sum_k \delta\left(t - t_j^k\right)$$

NMDA (slow excitation):

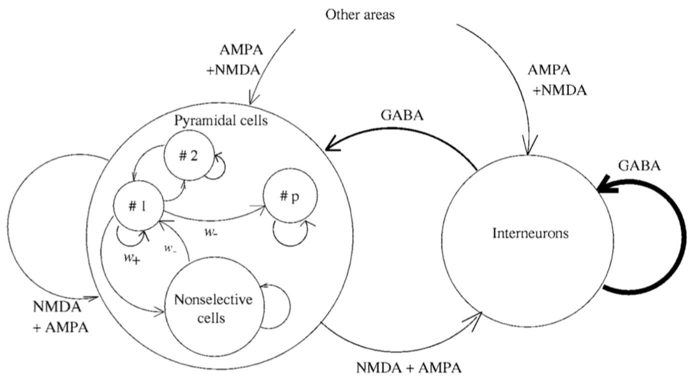
$$\frac{dx_j(t)}{dt} = -\frac{x_j(t)}{\tau_{\mathrm{NMDA,rise}}} + \sum_k \delta\left(t - t_j^k\right)$$

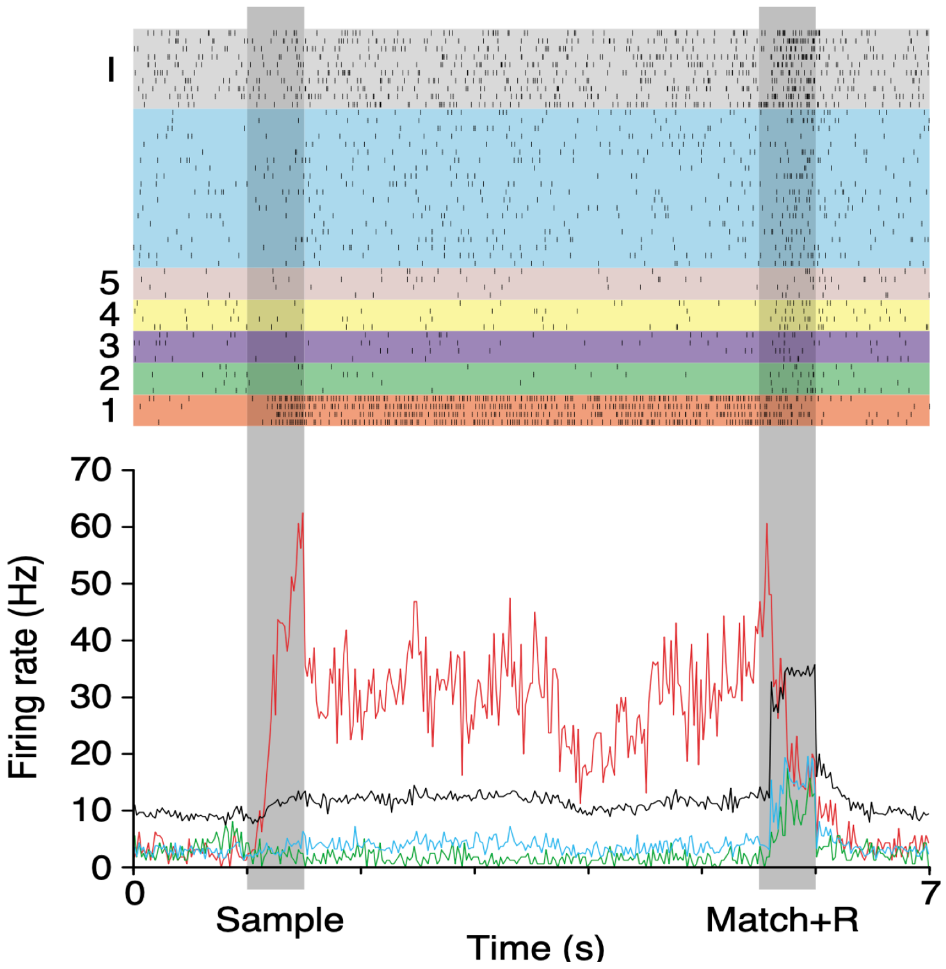
$$\frac{ds_j^{\mathrm{NMDA}}(t)}{dt} = -\frac{s_j^{\mathrm{NMDA}}(t)}{\tau_{\mathrm{NMDA,decay}}} + \alpha x_j(t)\left(1 - s_j^{\mathrm{NMDA}}(t)\right)$$

Brunel & Wang, 2001

$\tau_{NMDA,\,decay} = 100\,ms, \alpha = 0.5ms^{-1}, and\ \tau_{NMDA,\,rise} = 2\,ms$

Persistent activity in a realistic neural network model

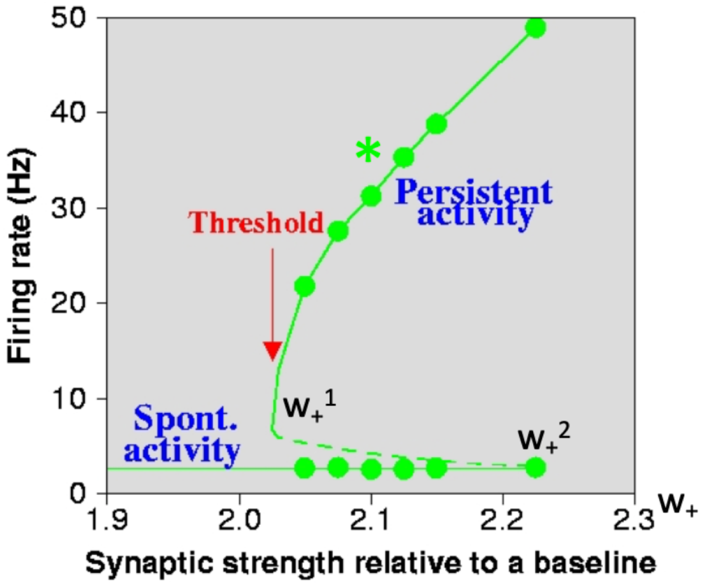


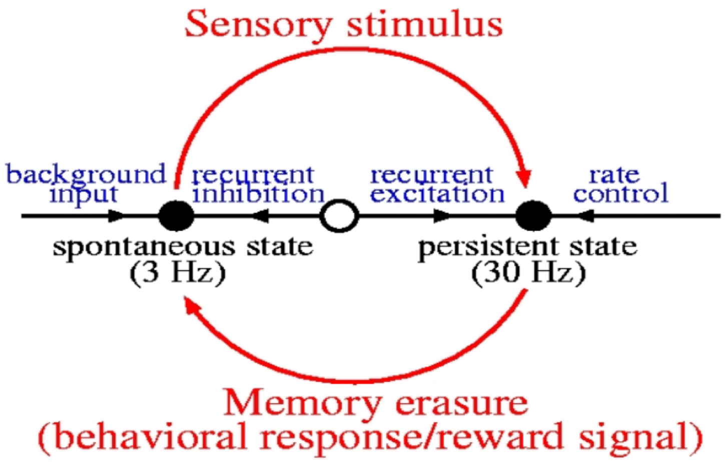


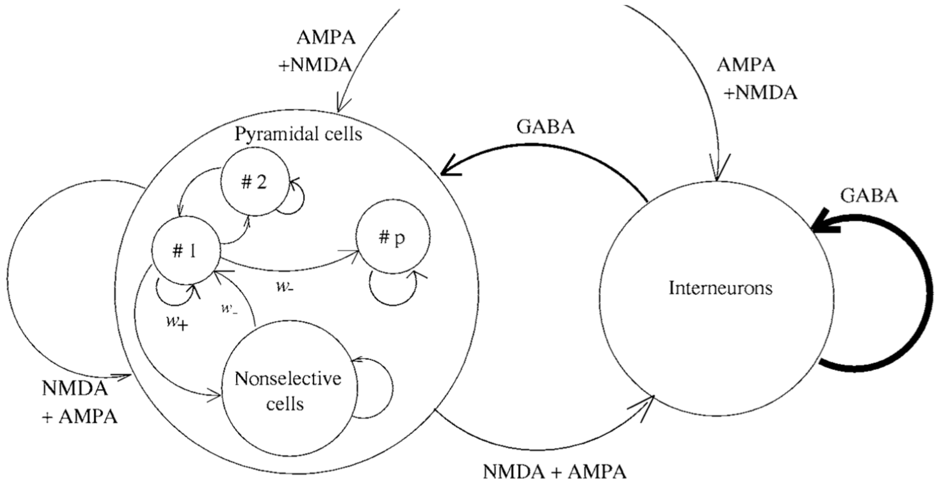
Stimulus-specific persistent activity arises
due to stronger recurrent connections (w+) within populations
of neurons that have the same preferred stimulus compared to
neurons with different preferred stimuli (w-)

Brunel & Wang, 2001

Bistability in the neural network model







Brunel & Wang, 2001; Wang, 2001

Limitations

- Only simulates prefrontal cortex. Recent evidence suggests that working memory relies on many interacting regions.
  - Step forward: simulate multiple interacting brain areas
- Simulates activity reaching a stable steady state during the delay. Activity is not always stable during the delay
  - Step forward: simulate more interacting processes on multiple timescales, such as short-term plasticity

Brunel & Wang, 2001; Wang, 2001

Reviewing learning objectives

- To understand the neural activity that produces working memory
  - Some neurons in prefrontal cortex fire throughout the delay period of working memory tasks. This may be a neural signature of working memory
- To understand the concept of bifurcations in nonlinear dynamical systems
  - In a nonlinear dynamical system, gradual changes to a parameter can lead to the sudden emergence of a new dynamical behaviour, if it passes a crucial point called a bifurcation point.
- To learn a neural network model of working memory
  - Brunel & Wang, 2001 showed how a neural network model with NMDA, AMPA and GABA receptors can reproduce stimulus-specific persistent activity like in working memory experiments.

Thank you!

- Contact me on Teams!