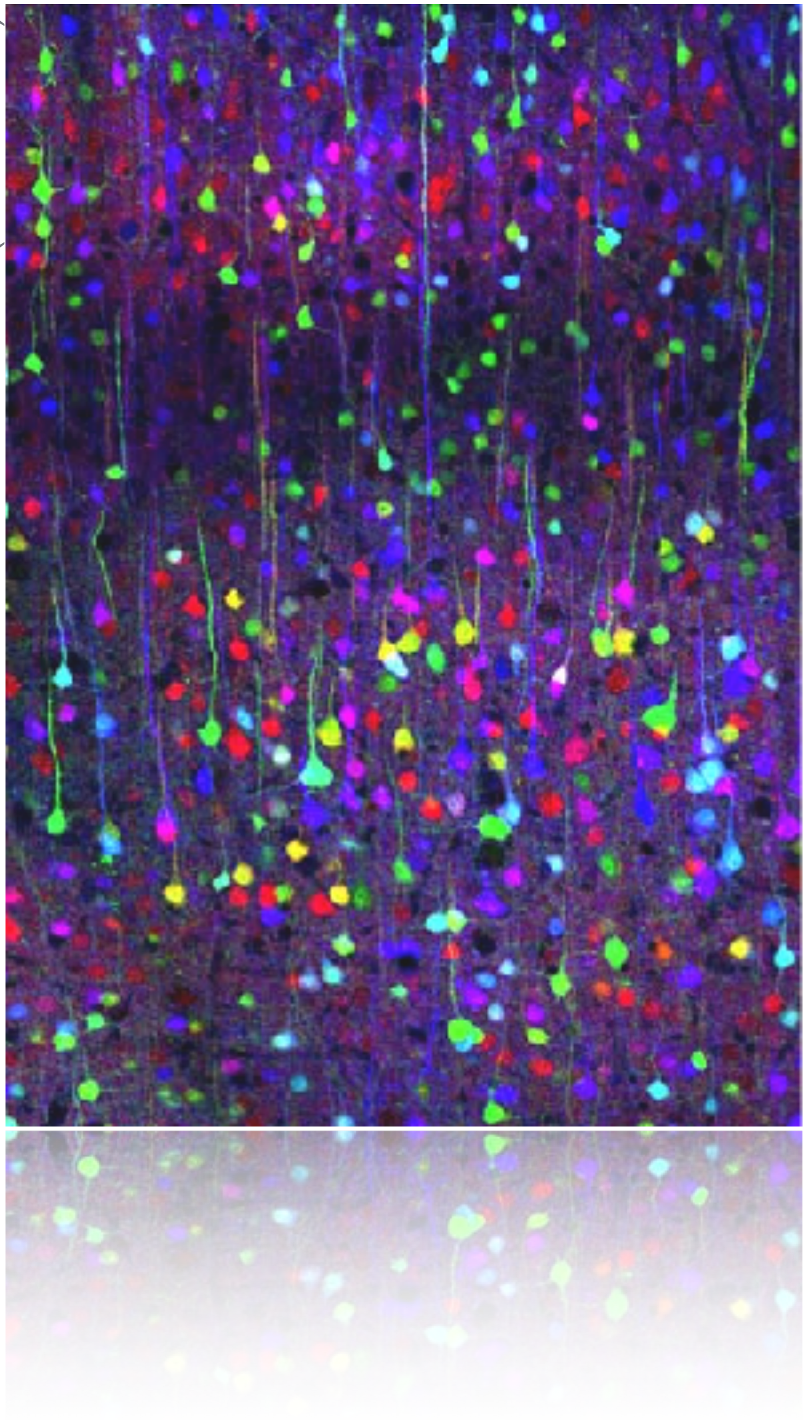
Computational Neuroscience 2018/2019

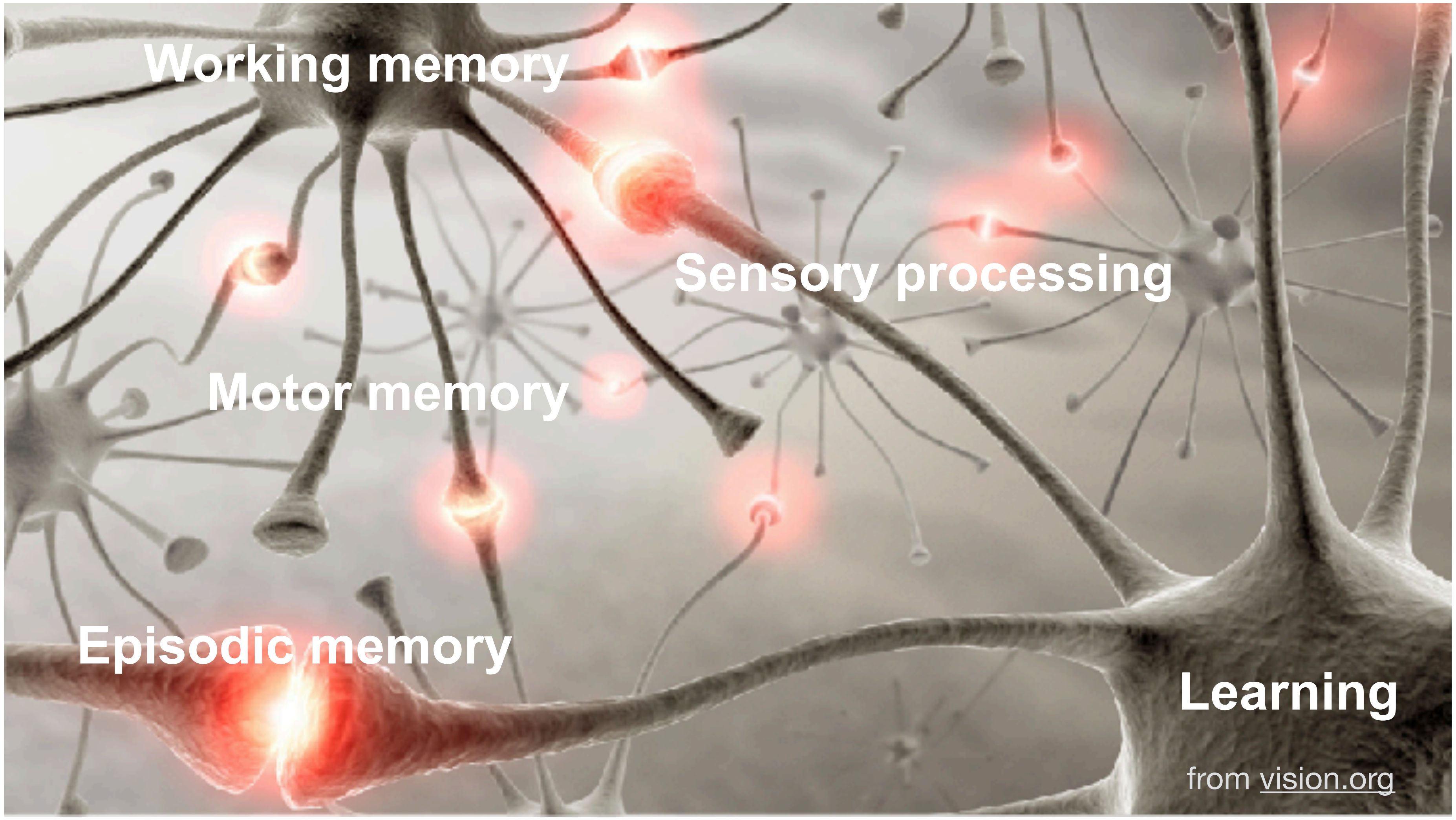
University of BRISTOL

Brainbow (Litchman Lab)

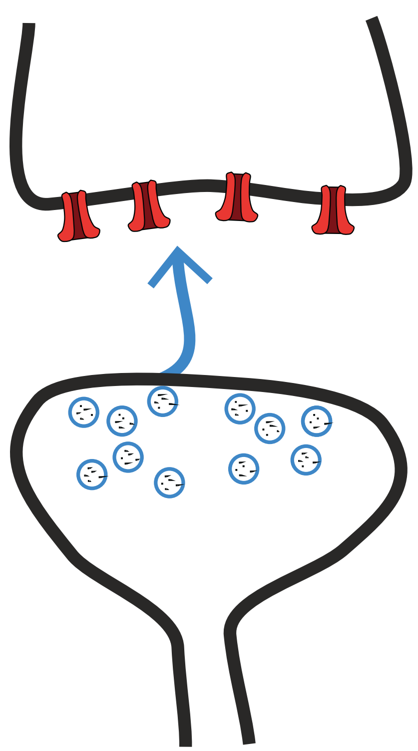


Lecture 16
Synaptic plasticity:
Short-term synaptic plasticity

Synaptic plasticity
underlies memory and learning



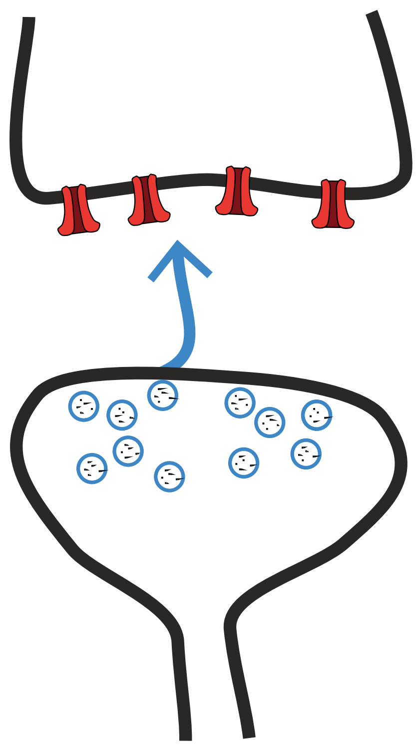
Synaptic plasticity

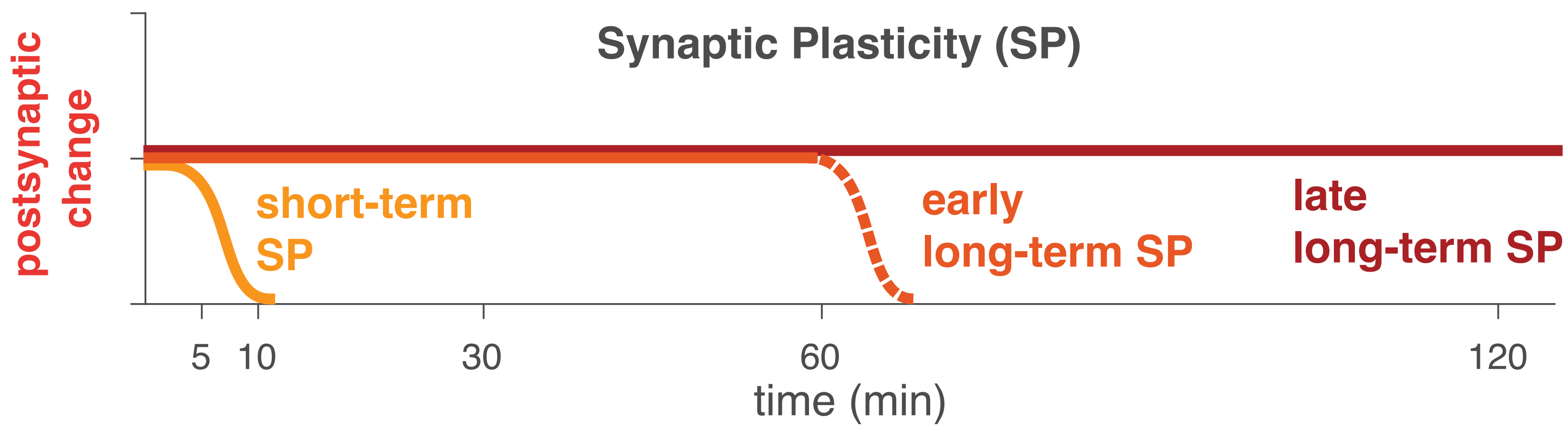


Synaptic plasticity:
Multiple timescales and locations

Synapses can change **postsynaptically**

(from a few seconds (**short-term**) to tens of minutes, hours (**long-term**) or even days/years!):

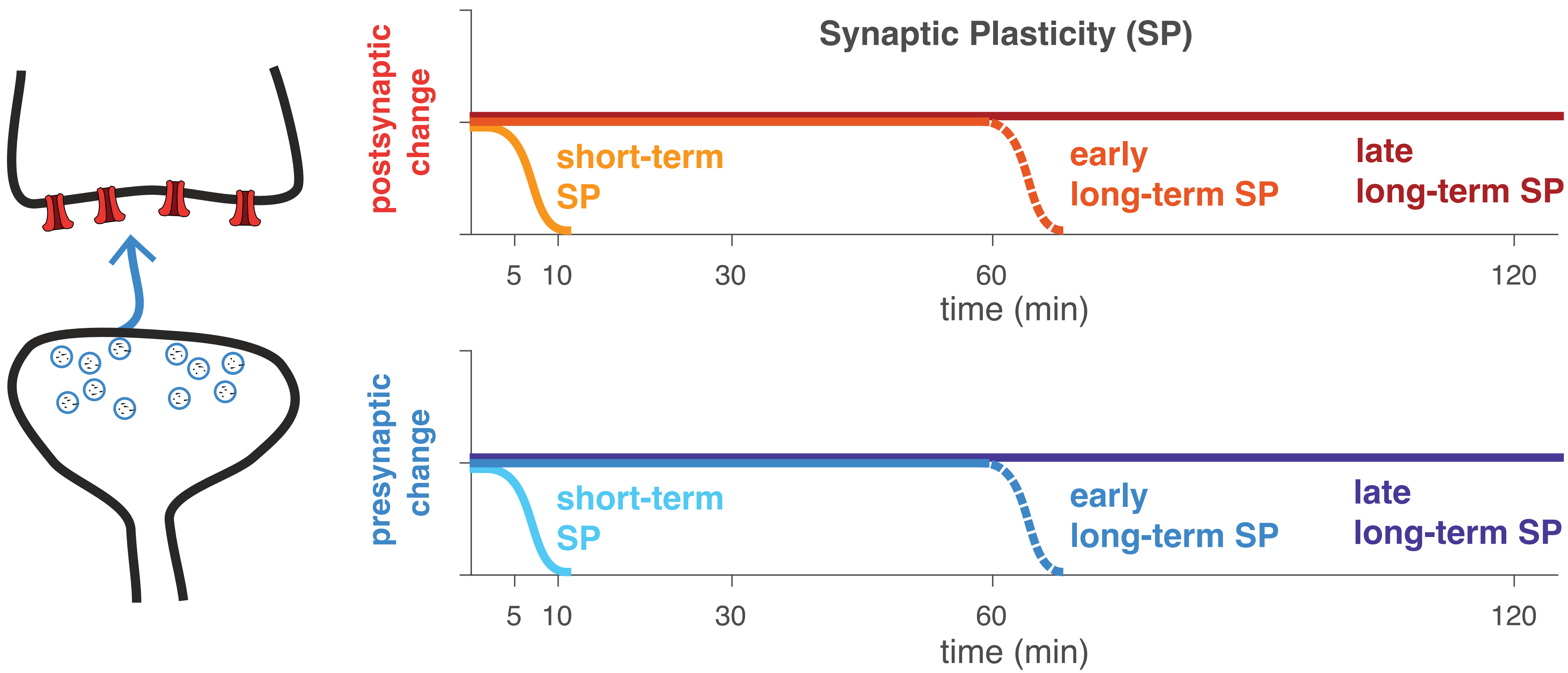




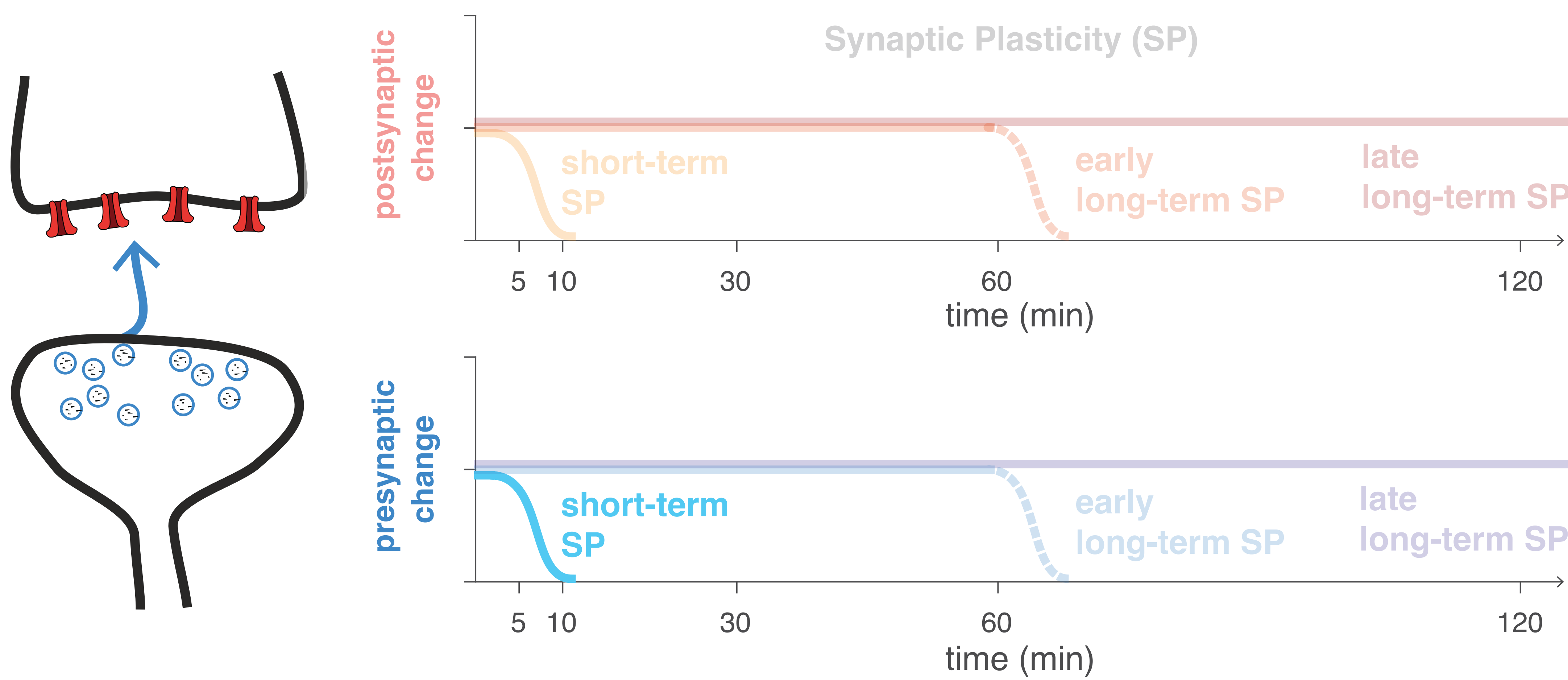
Synaptic plasticity: Multiple timescales and locations

But they can also change **presynaptically**

(from a few seconds (**short-term**) to tens of minutes, hours (**long-term**) or even days/years!):



Presynaptic
Short-term synaptic plasticity



Abbott & Regehr Nature 2004

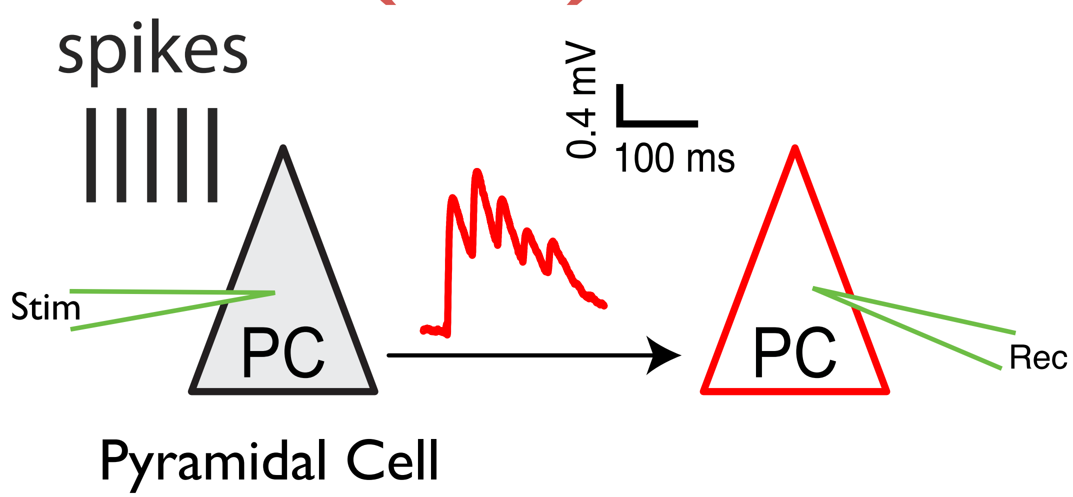
Outline

Short-term synaptic plasticity (STP)

1. **The two main types**
2. **Models: Tsodyks-Markram and other models**
3. **Functions**
   - 3.1. **Network dynamics**
   - 3.2. **Theory of working memory**

Two main types of short-term synaptic plasticity

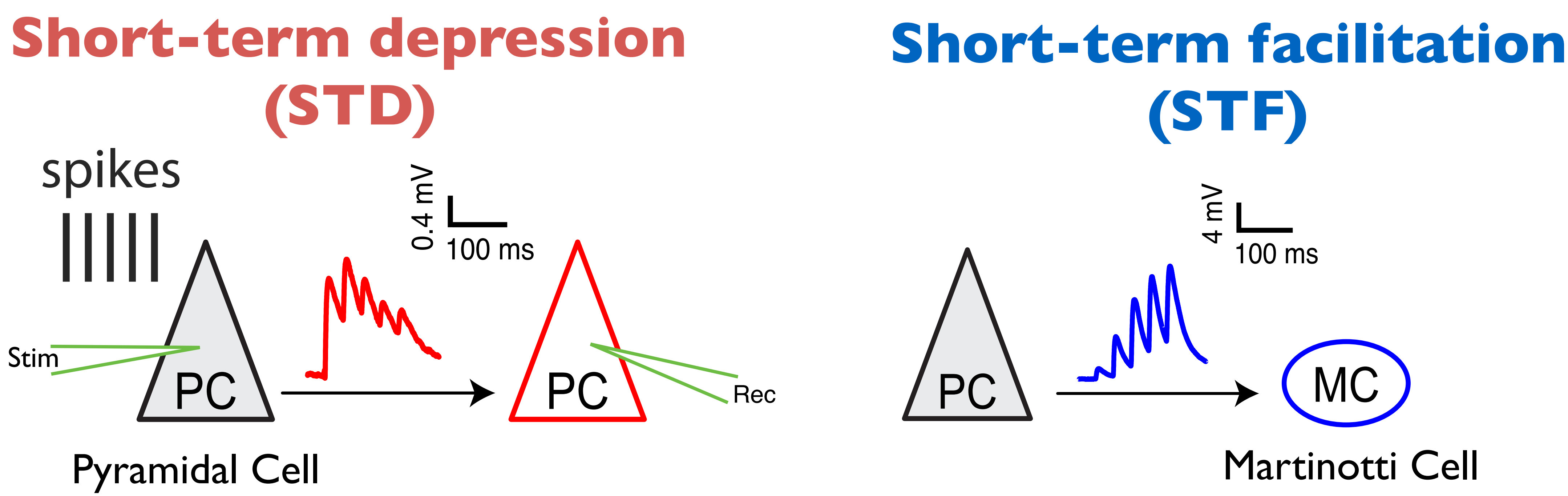
Short-term depression (STD)



Tsodyks and Markram, PNAS 1997; Costa et al. 2013 Frontiers

Abbott & Regehr Nature 2004

Two main types of short-term synaptic plasticity



Tsodyks and Markram, PNAS 1997; Costa et al. 2013 Frontiers

Abbott & Regehr Nature 2004

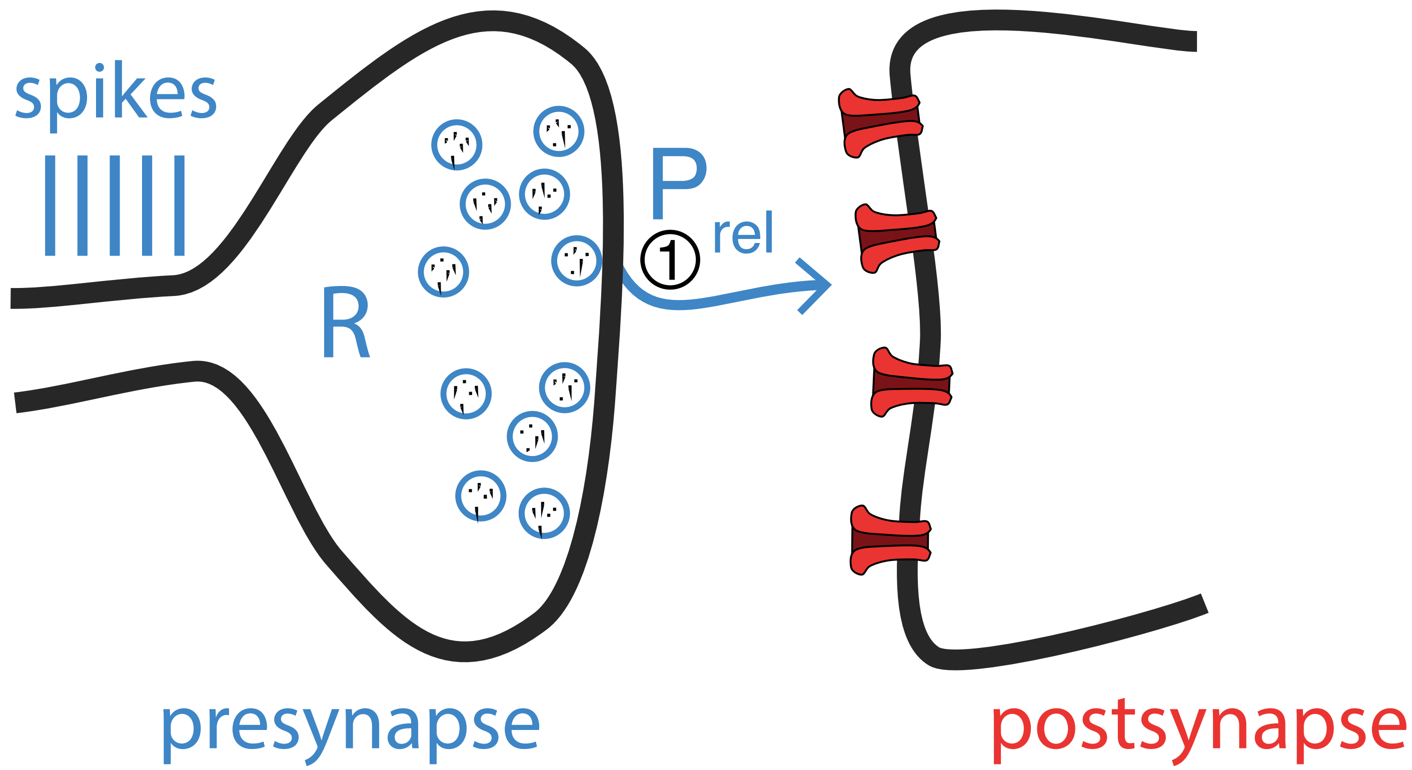
Models of short-term synaptic plasticity

Models of short-term synaptic plasticity (STP)

1. **Phenomenological models**
    1. Varela model [more abstract model, Varela et al. JNeurosci 1997]
    2. Markram-Tsodyks (STD and STF) [closer to biology]: Tsodyks, Markram et al. PNAS 1997/1998

2. **Molecular models**
    1. Pan and Zucker Neuron 2009

A phenomenological model of STD:
Tsodyks-Markram model



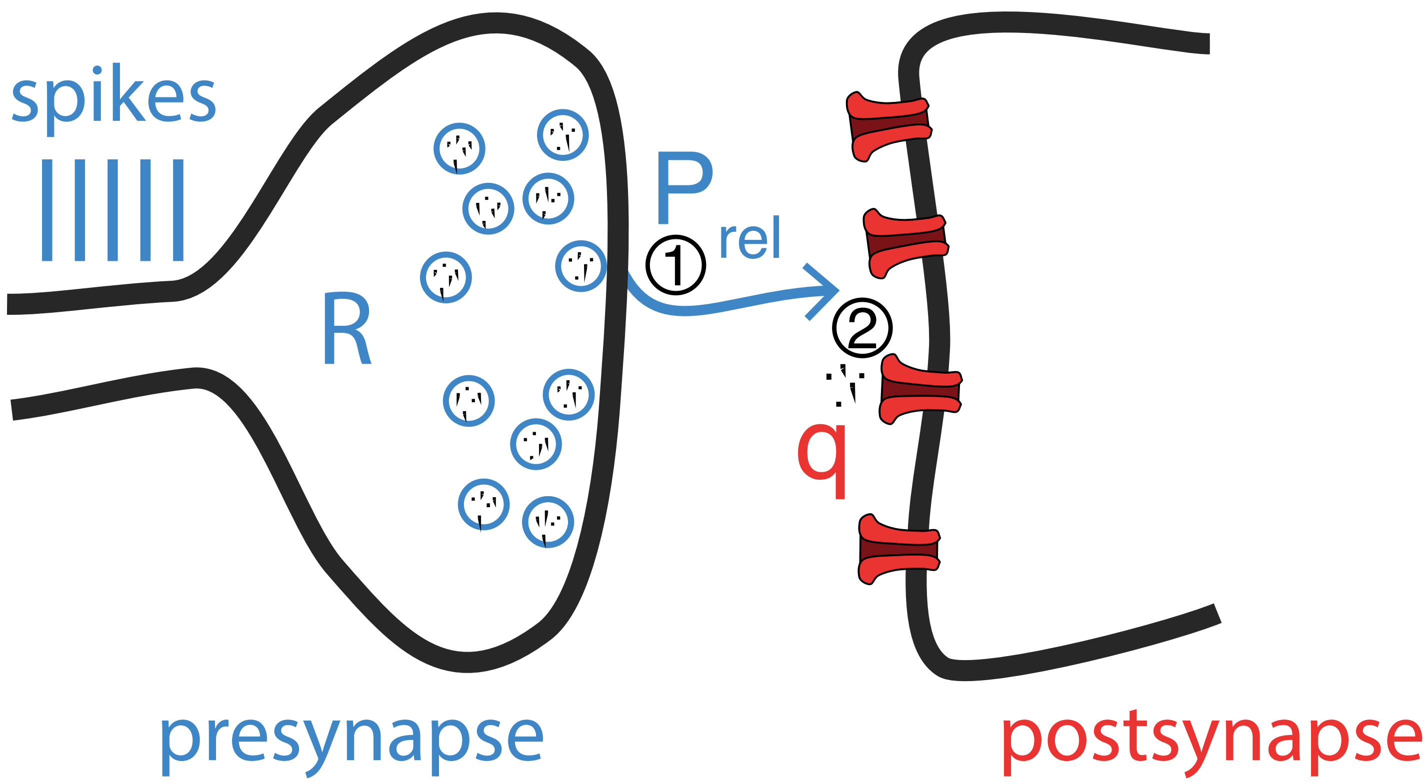
Abstracted out of molecular 'details'!

1: R vesicles are released with probability **P_rel**
Average release = R x P_rel

Tsodyks, Markram et al. PNAS 1997/1998;
Regehr CSH 2012;
Costa et al. Frontiers 2013

Note:
R is the fraction of vesicles available per release site.
Here we assume the number of release sites to be 1 (i.e. **N=1**), see previous lecture.

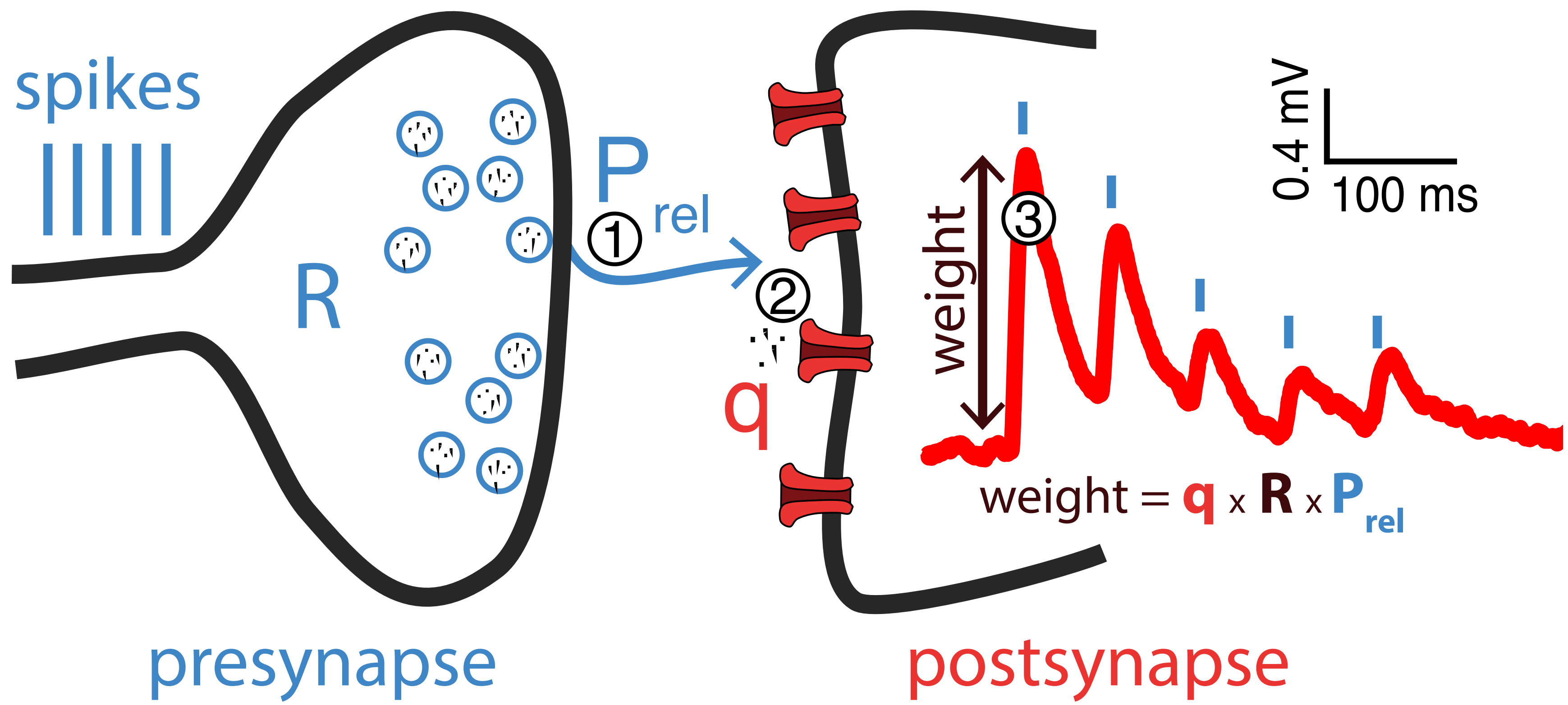
A phenomenological model of STD:
Tsodyks-Markram model



2: Released neurotransmitters bind to postsynaptic receptors causing a response with amplitude **q**

Tsodyks, Markram et al. PNAS 1997/1998;
Regehr CSH 2012;
Costa et al. Frontiers 2013

A phenomenological model of STD:
Tsodyks-Markram model

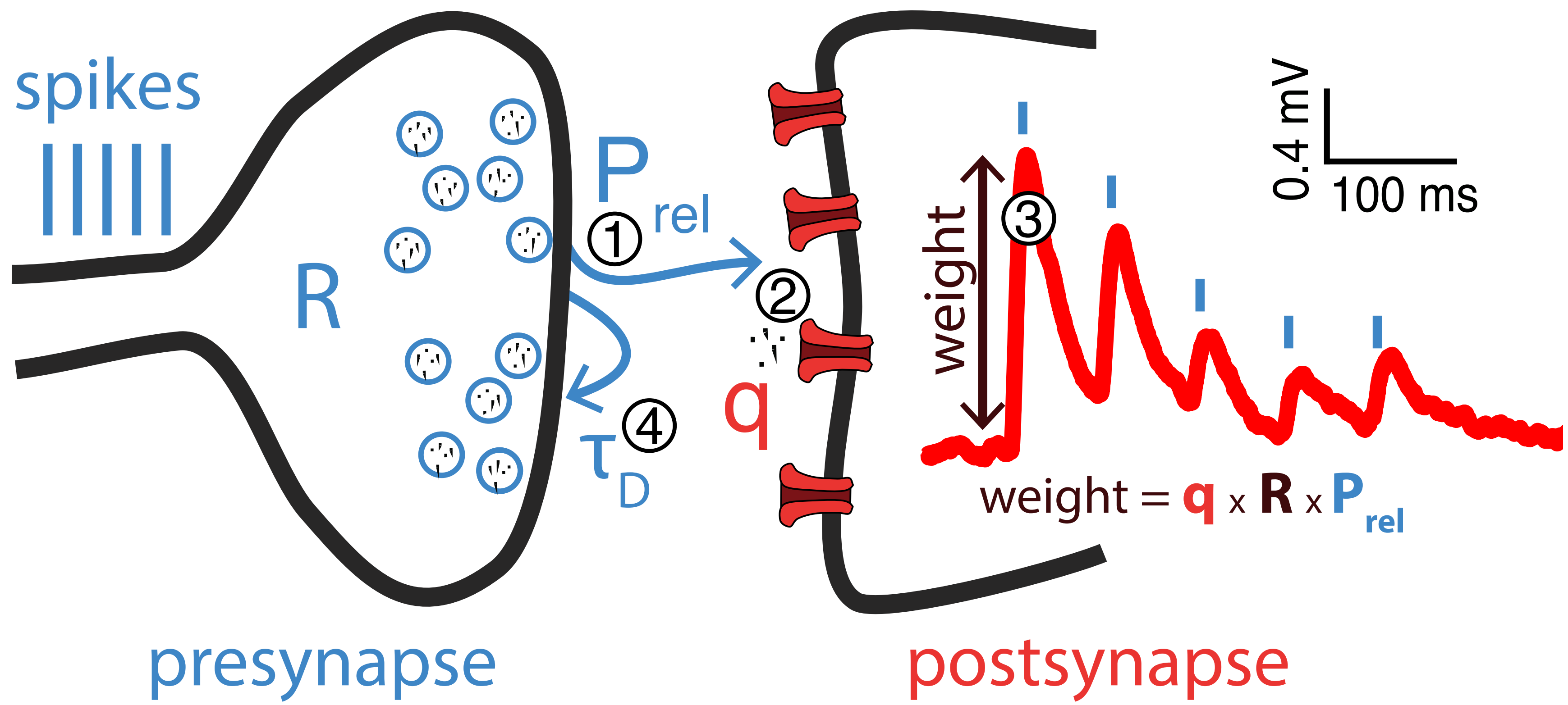


3: The final synaptic response (or weight) is then equal to q x R x P_rel

Note: This model ignores the stochastic nature of synapses and different release sites (*N* in the previous lecture).

Tsodyks, Markram et al. PNAS 1997/1998;
Regehr CSH 2012;
Costa et al. Frontiers 2013

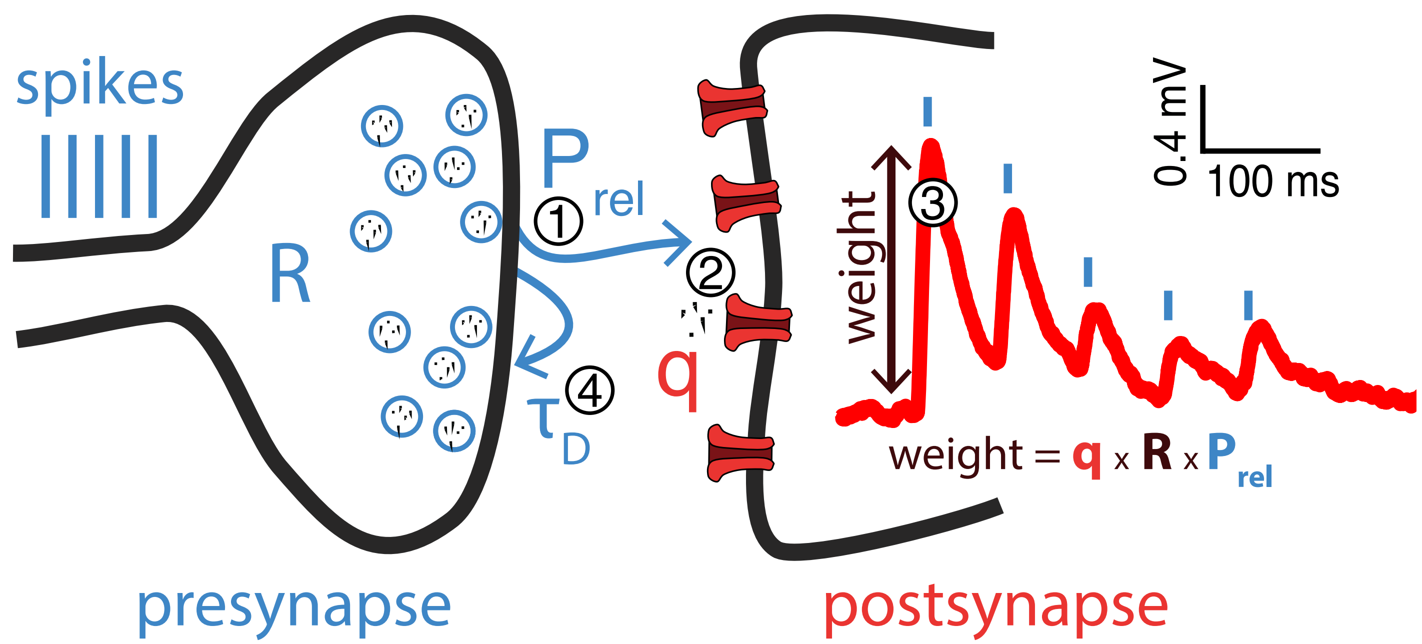
A phenomenological model of STD:
Tsodyks-Markram model



4: At the same vesicles are recycled with a time constant **tau_D**, which leads to short-term depression before the vesicles (**R**) are fully recovered

Tsodyks, Markram et al. PNAS 1997/1998;
Regehr CSH 2012;
Costa et al. Frontiers 2013

A phenomenological model of STD:
Tsodyks-Markram model

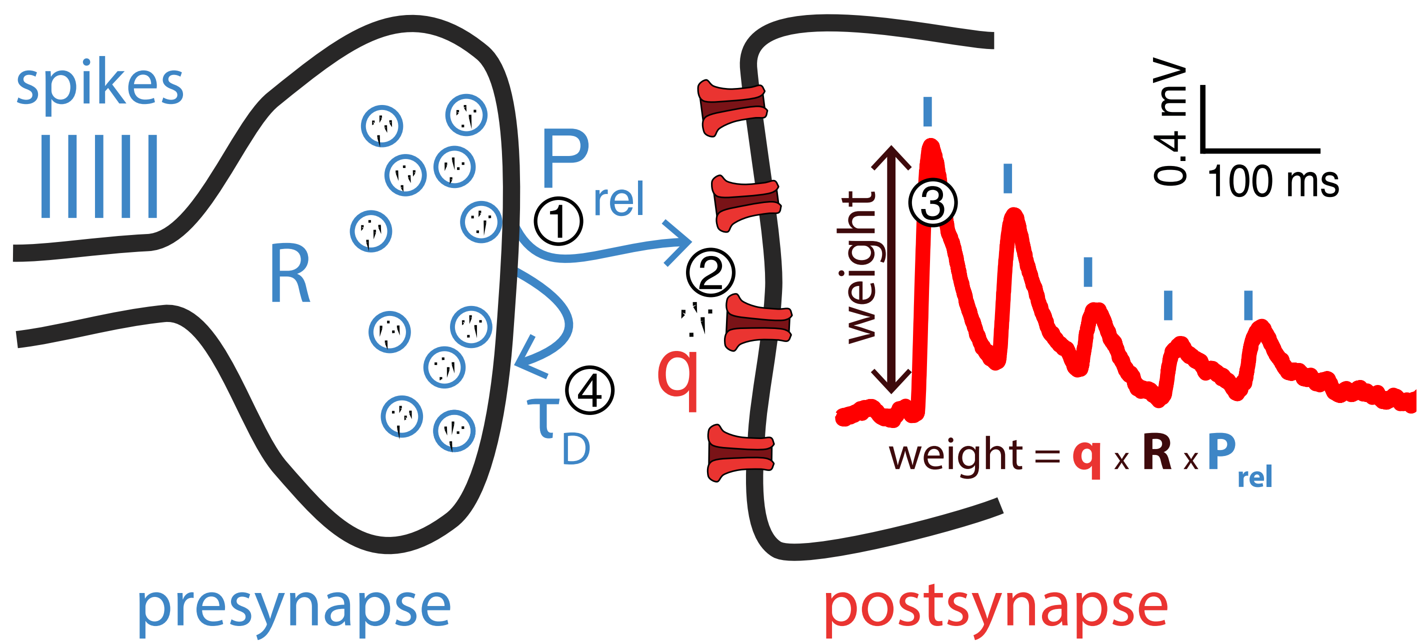


Differential equation that **models the number of vesicles available:**

$$\frac{dR}{dt} = \qquad - RP_r\delta_{\text{spike}}$$

Tsodyks, Markram et al. PNAS 1997/1998;

A phenomenological model of STD:
Tsodyks-Markram model



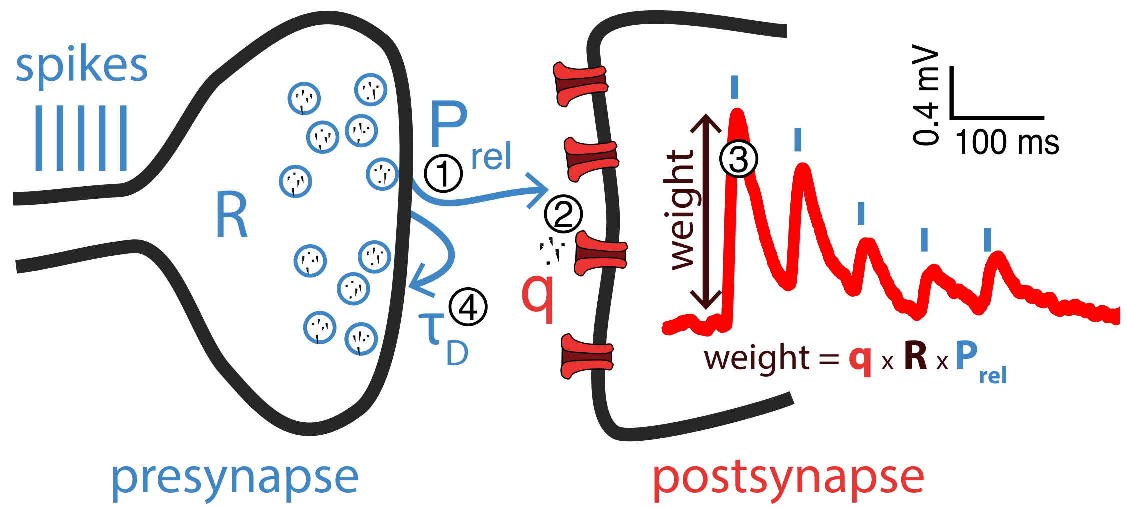
Differential equation that **models the number of vesicles available:**

$$\frac{dR}{dt} = \frac{1 - R}{\tau_D} - RP_r\delta_{\text{spike}}$$

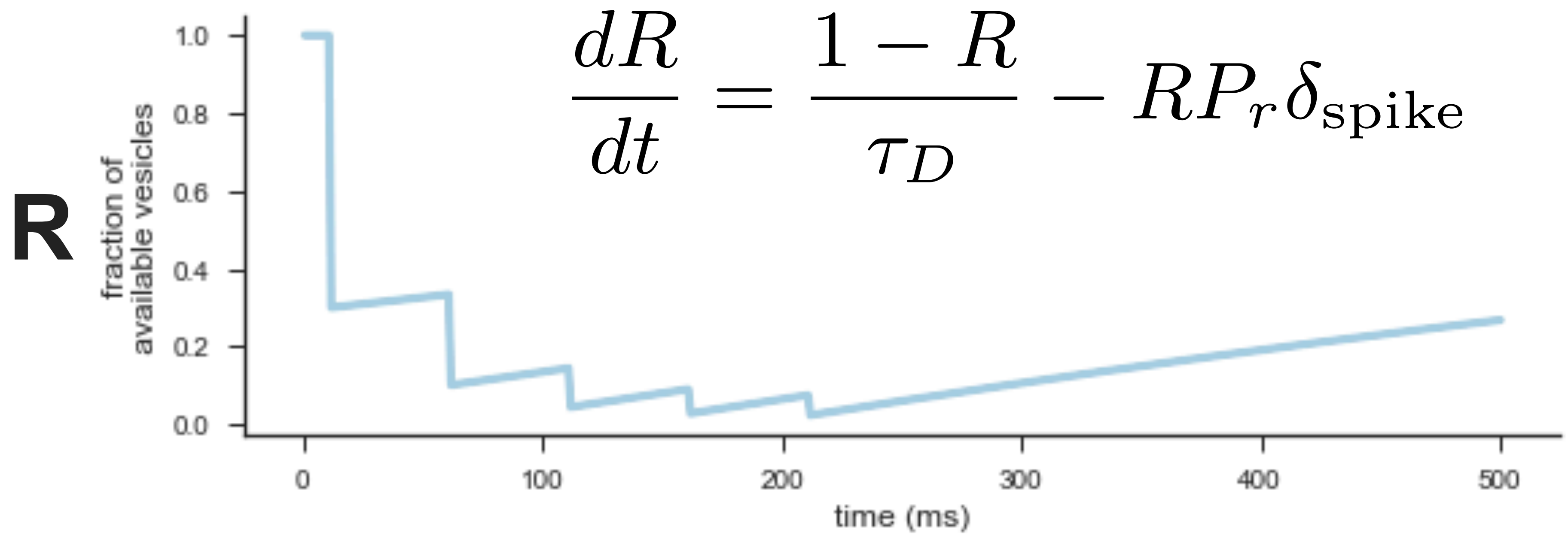
Two parameters: **tau_D** and **P_r**

Tsodyks, Markram et al. PNAS 1997/1998;

A phenomenological model of STD:
Tsodyks-Markram model

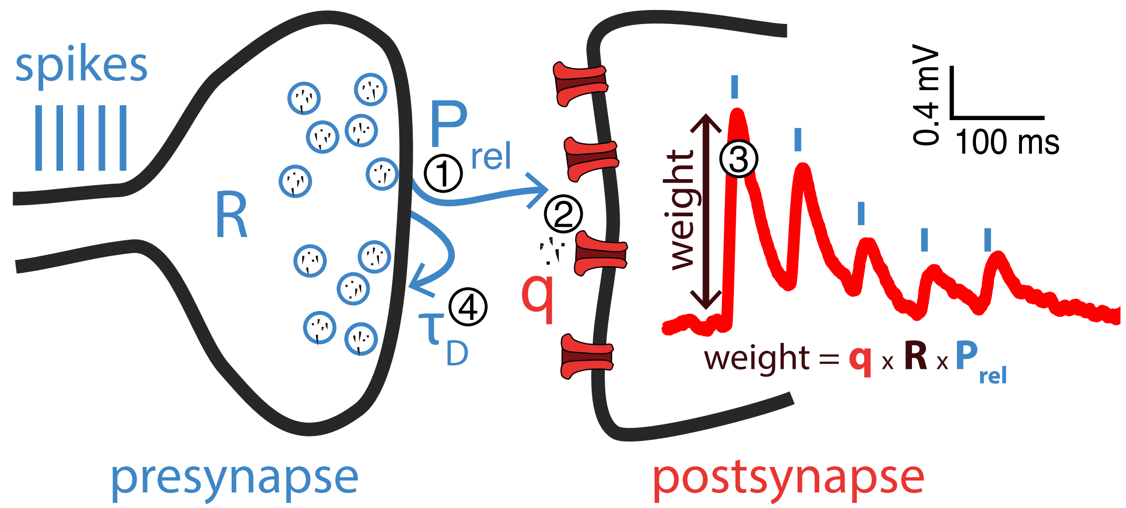


$$\frac{dR}{dt} = \frac{1-R}{\tau_D} - RP_r\delta_{\text{spike}}$$

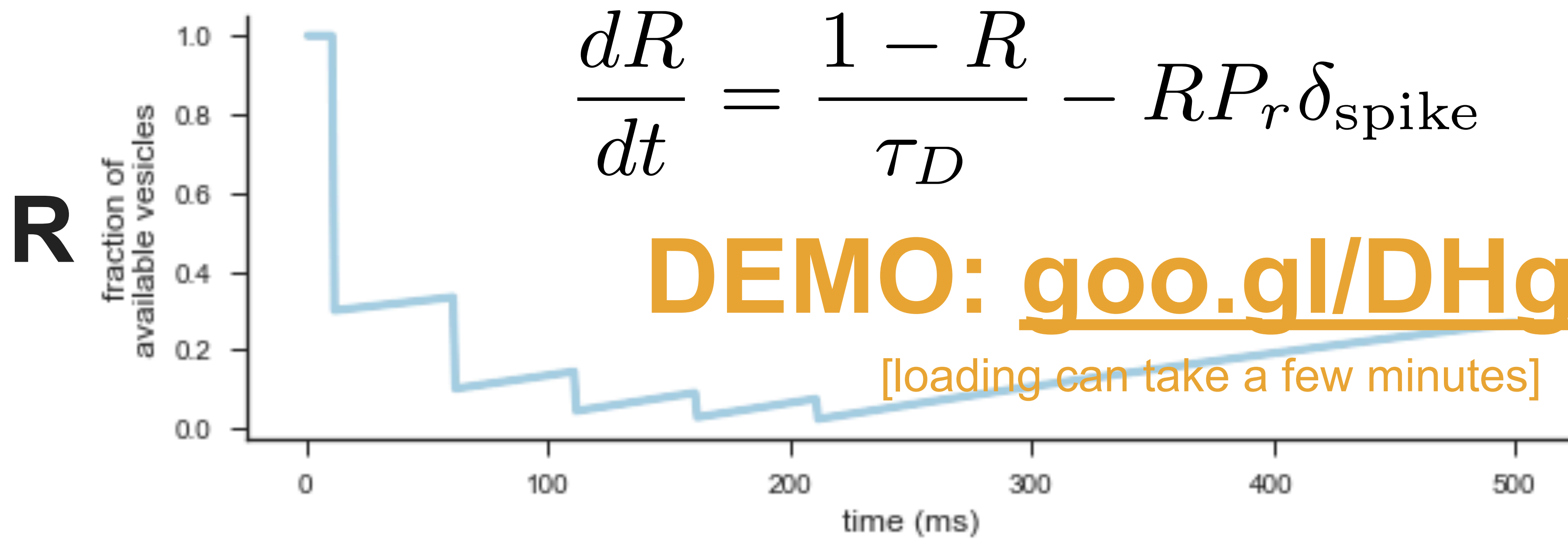


Tsodyks, Markram et al. PNAS 1997/1998;

A phenomenological model of STD:
Tsodyks-Markram model



$$\frac{dR}{dt} = \frac{1-R}{\tau_D} - RP_r\delta_{\text{spike}}$$

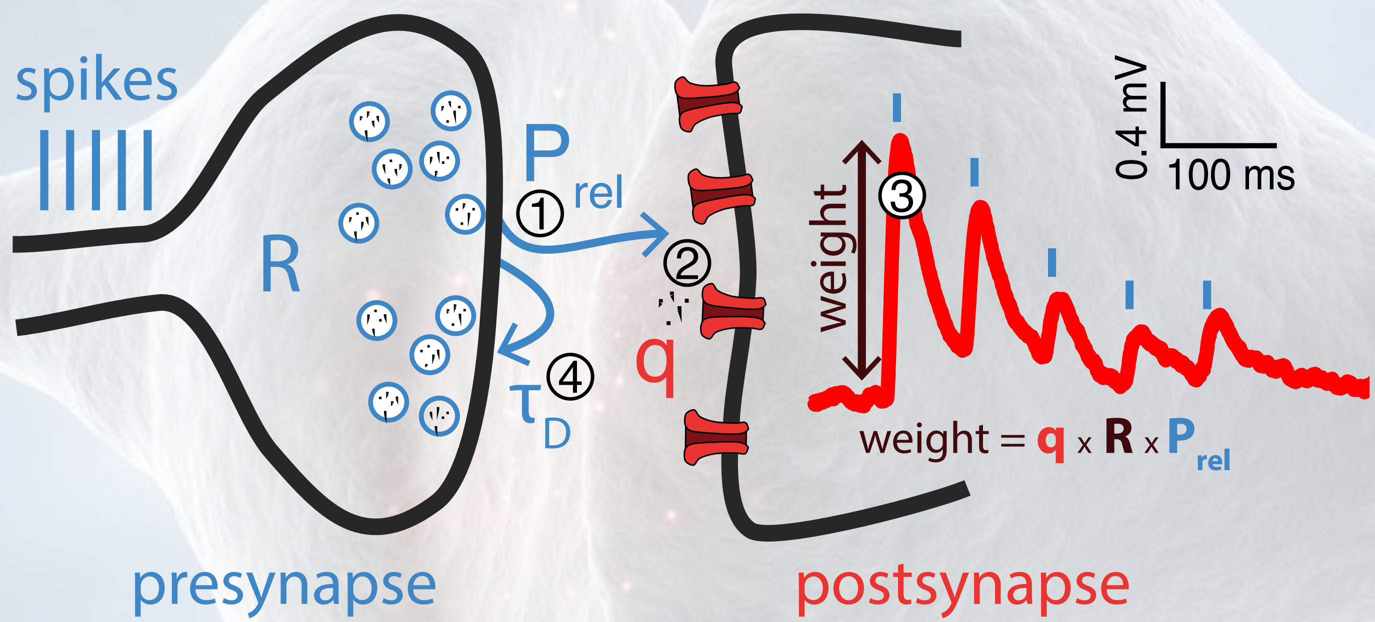


DEMO: goo.gl/DHgNsA

[loading can take a few minutes]

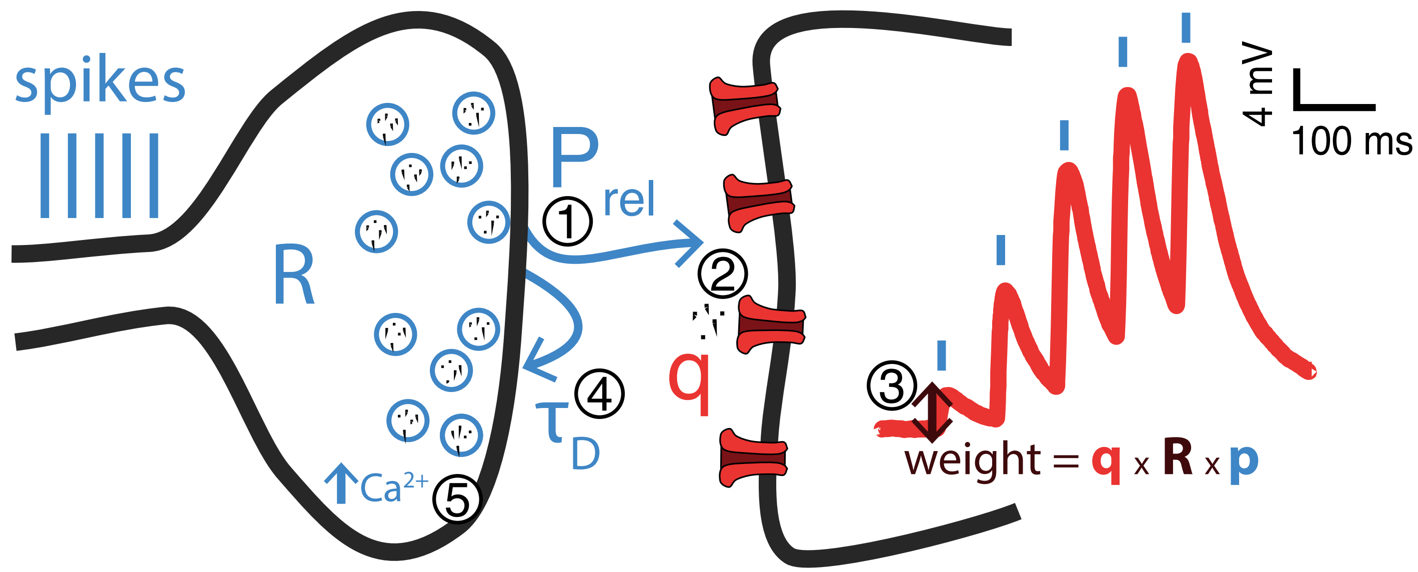
Tsodyks, Markram et al. PNAS 1997/1998;

Questions?



spikes
R
P rel
①
②
③
④
τ D
q
weight
0.4 mV
100 ms
weight = q x R x P rel
presynapse
postsynapse

A phenomenological model of STF:
Tsodyks-Markram model with facilitation



5: Calcium build up on the presynaptic side, leads to increased release probability *p*

Number of release vesicles:

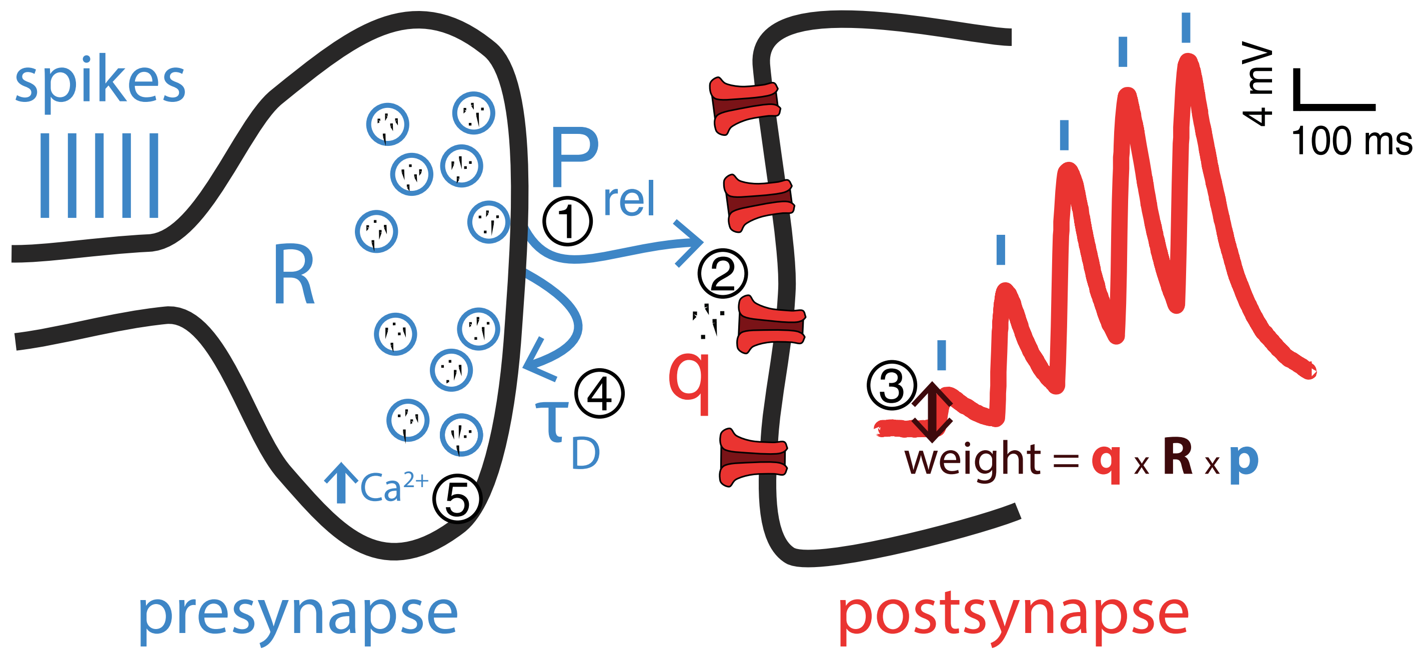
$$\frac{dR}{dt} = \frac{1-R}{\tau_D} - Rp\delta_{\text{spike}}$$

Dynamic release probability:

$$\frac{dp}{dt} = \qquad + (1-p)\delta_{\text{spike}}$$

Tsodyks, Markram et al. PNAS 1997/1998;

A phenomenological model of STF:
Tsodyks-Markram model with facilitation



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Number of release vesicles:

$$\frac{dR}{dt} = \frac{1-R}{\tau_D} - Rp\delta_{\text{spike}}$$

Dynamic release probability:

$$\frac{dp}{dt} = \frac{P_r - p}{\tau_F} + (1-p)\delta_{\text{spike}}$$

Tsodyks, Markram et al. PNAS 1997/1998;

Group discussion

[groups of 2-3 (5 min)]

- What benefits might *short-term plasticity* have for the brain?

Hint: Remember that the brain is a dynamical system!

Outline

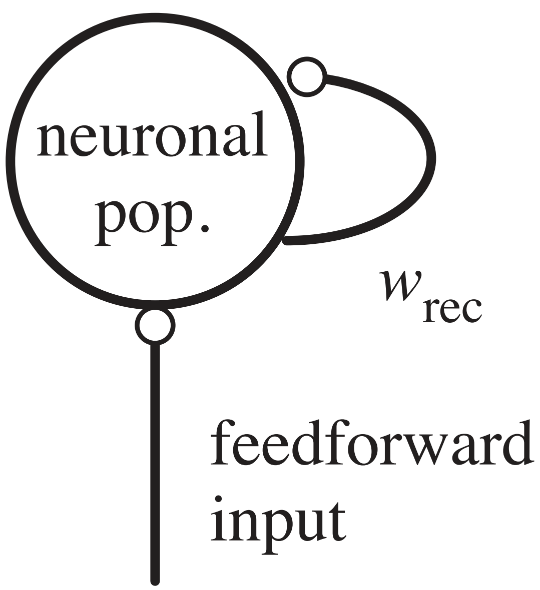
Short-term synaptic plasticity (STP)

1. The two main types
2. Models: Tsodyks-Markram and other models
3. **Functions**
   - **3.1. Network dynamics**
   - **3.2. Theory of working memory**

Summary: short-term plasticity (part 1)

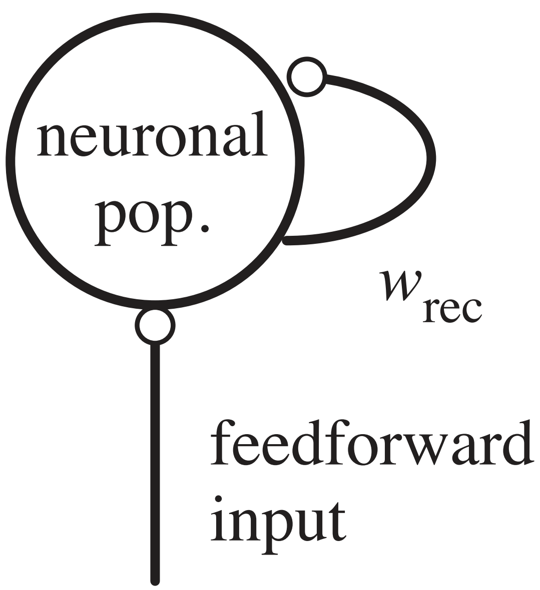
1. Lasts for up to tens of seconds
2. Two types: short-term depression and facilitation
3. Phenomenological and molecular models
4. Markram-Tsodyks model is a popular model with versions that can capture STD and STF

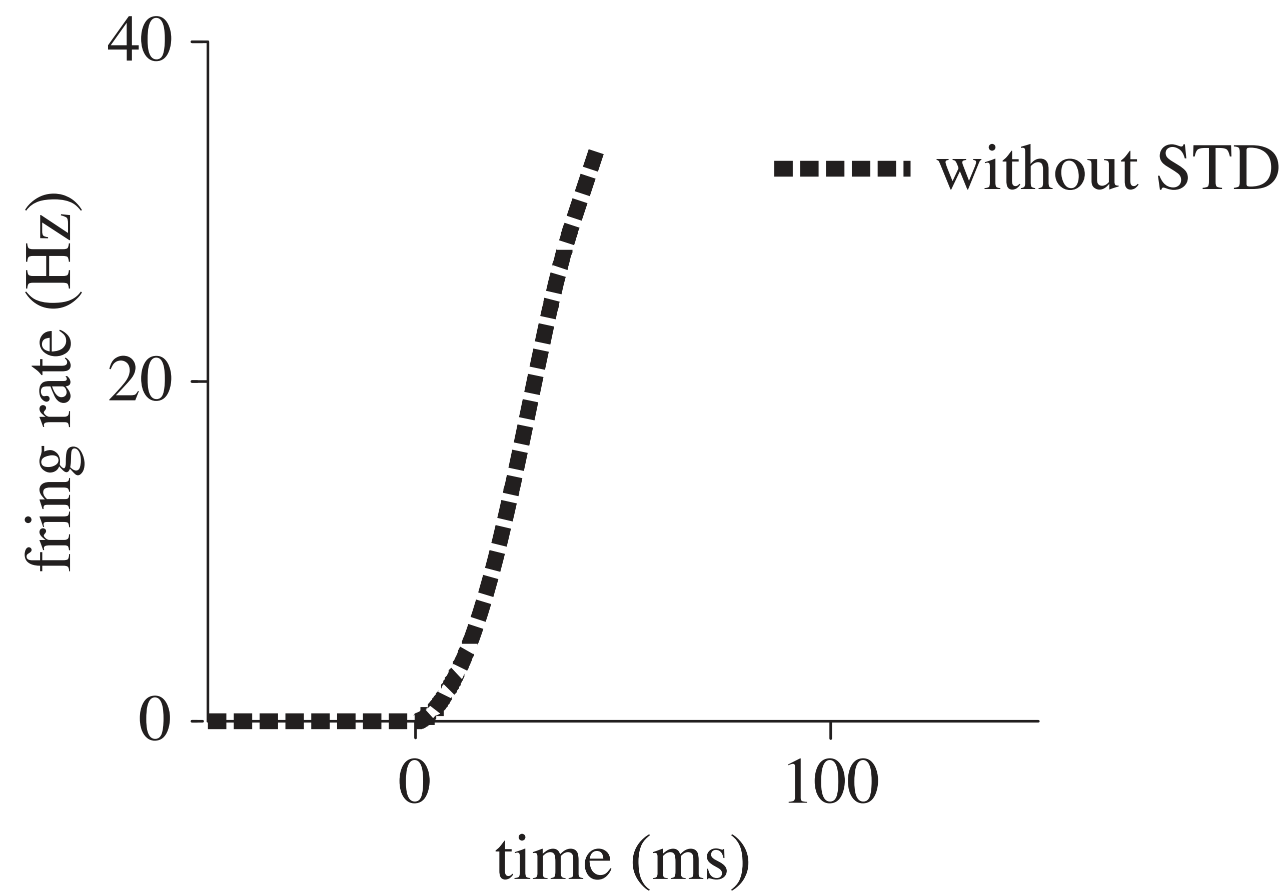
Short-term depression helps prevent seizure-like dynamics



Costa et al. Phil. Trans. R. Soc. 2017
Sussillo et al. JNeurophysiol. 2007
and several others..

Short-term depression helps prevent seizure-like dynamics





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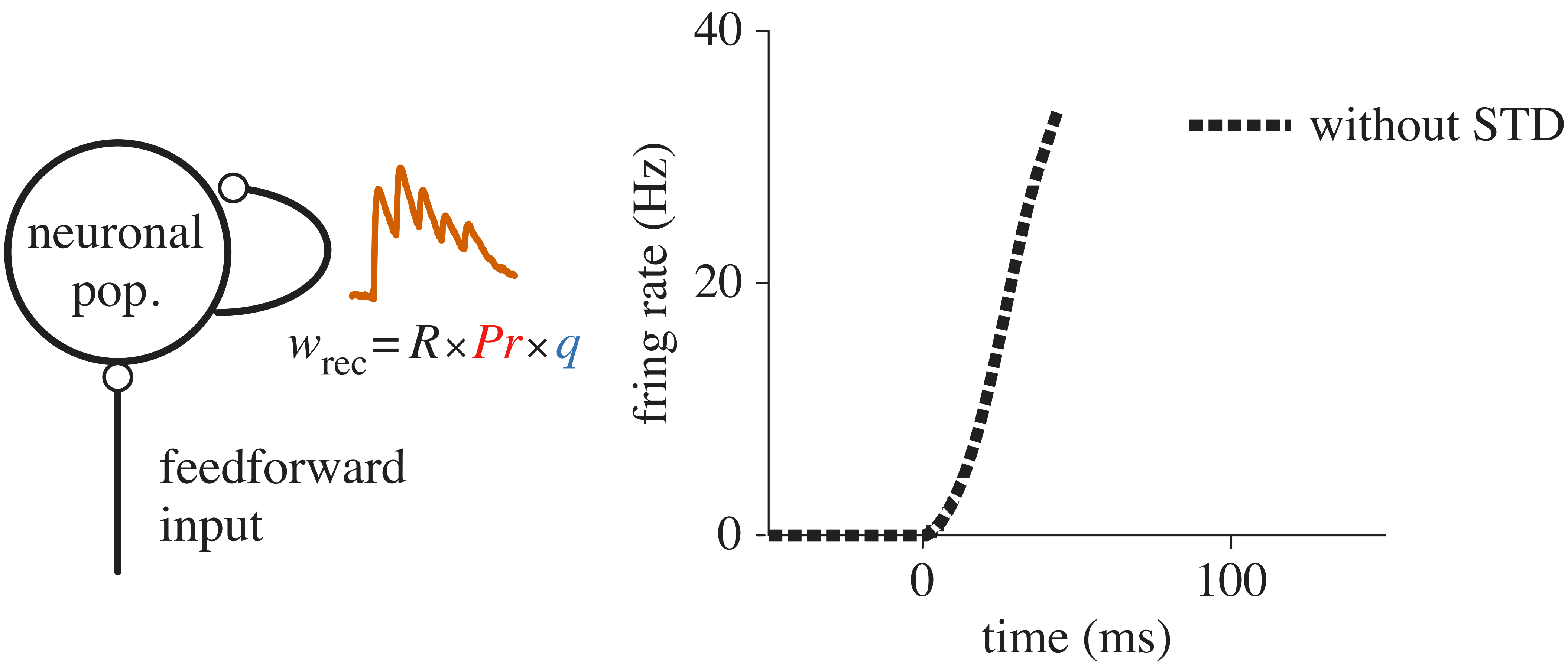

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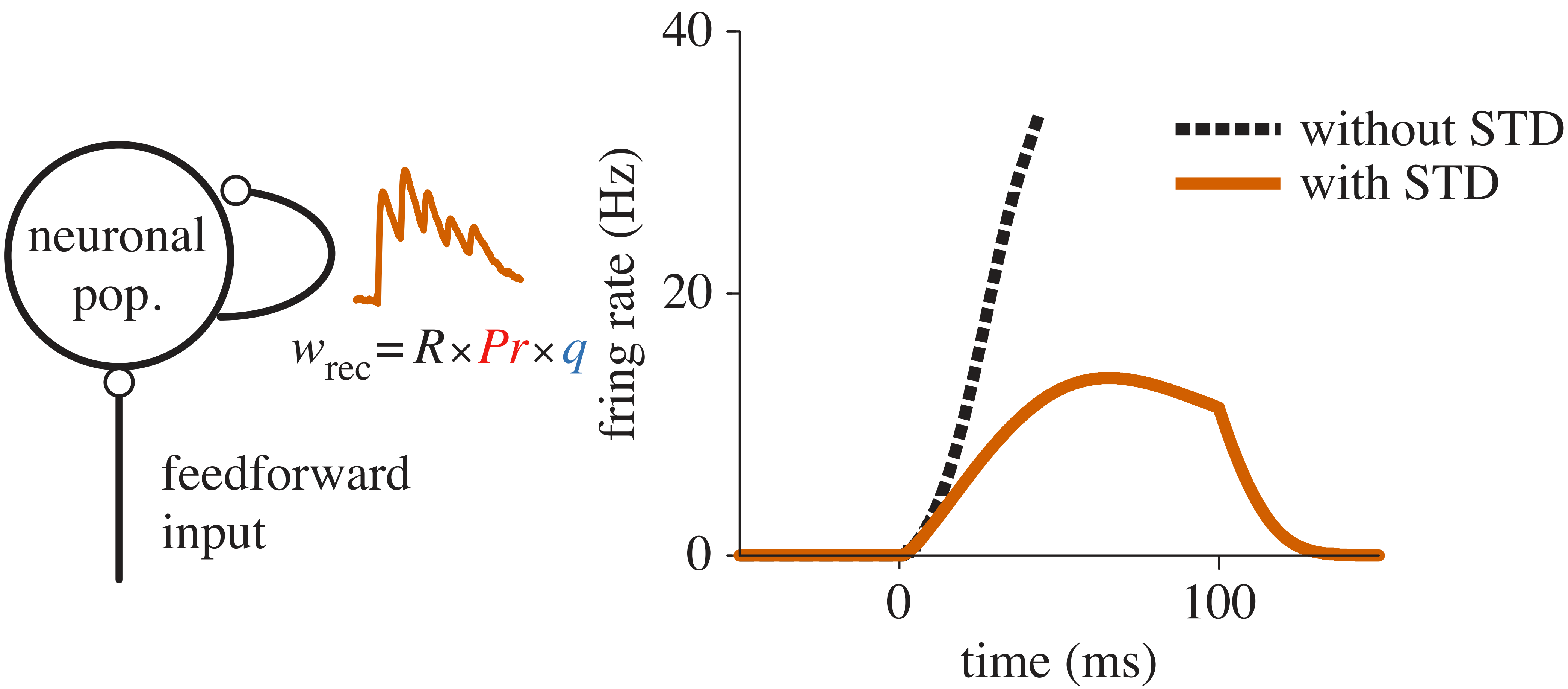


Costa et al. Phil. Trans. R. Soc. 2017
Sussillo et al. JNeurophysiol. 2007
and several others..

Short-term facilitation as a theory of working memory

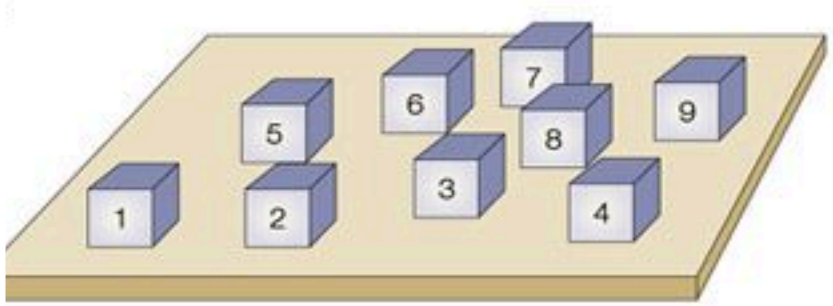
Working memory is our ability to keep an item in memory for a short period of time, with very limited capacity (usually up to 5-10 different items).

Note: Working memory is key for reasoning: our ability to link different sets of information together.

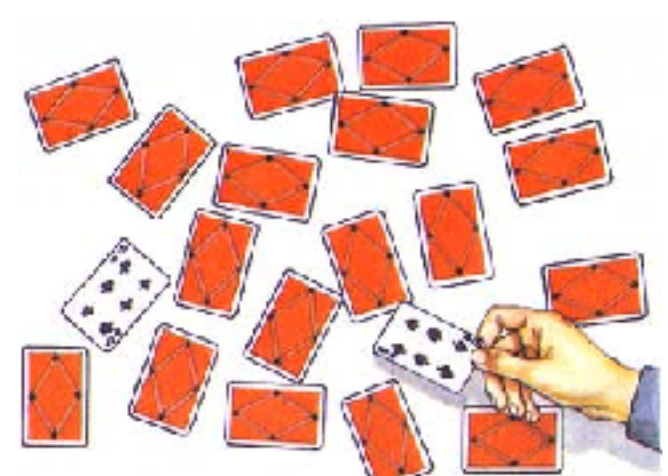
Examples: Remembering a phone number, while driving.
Where are all your lectures for the day?
Or these particular tasks:

Corsi block tapping task:

recall the order of tapping on the blocks

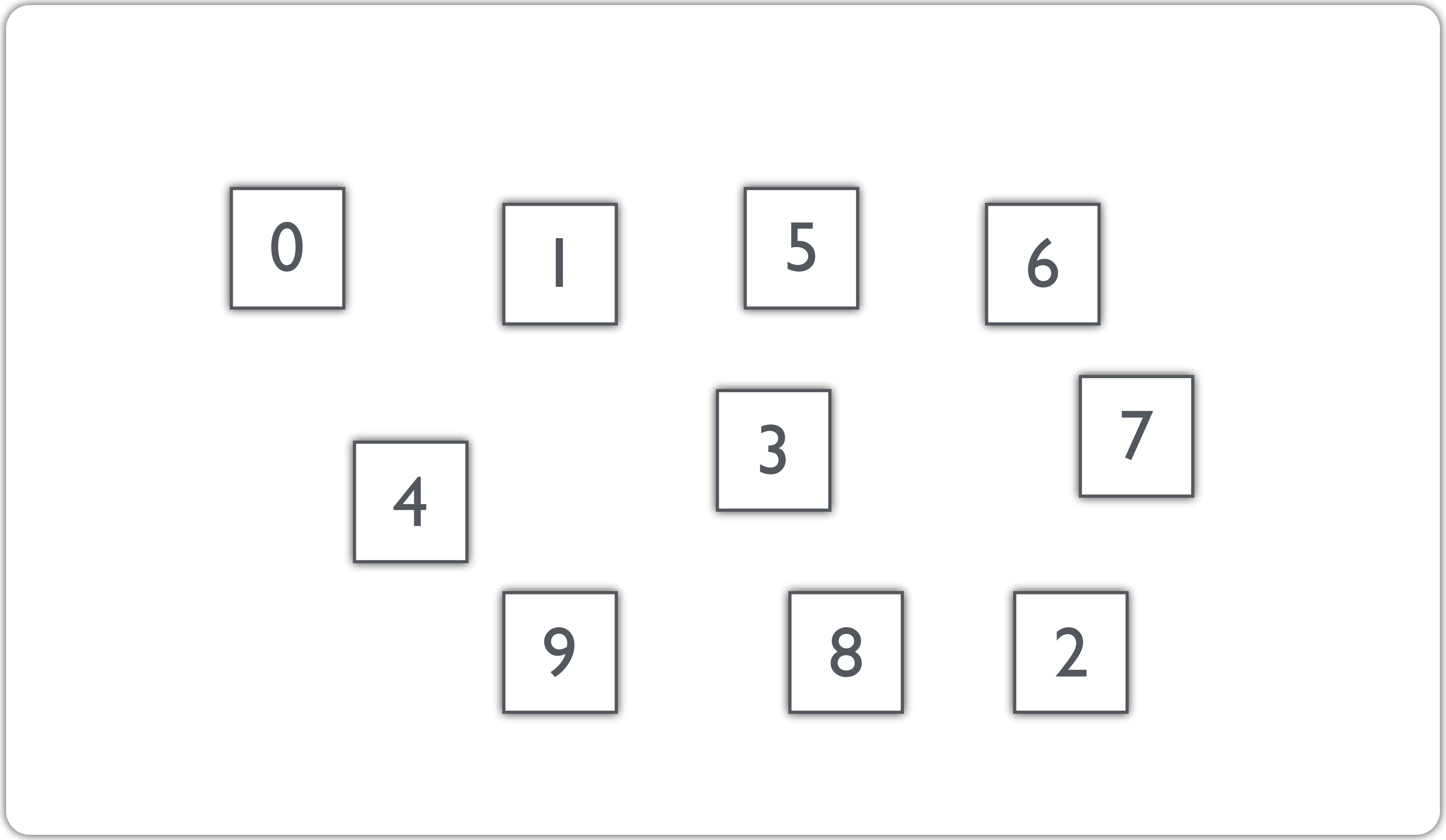


Card matching game:

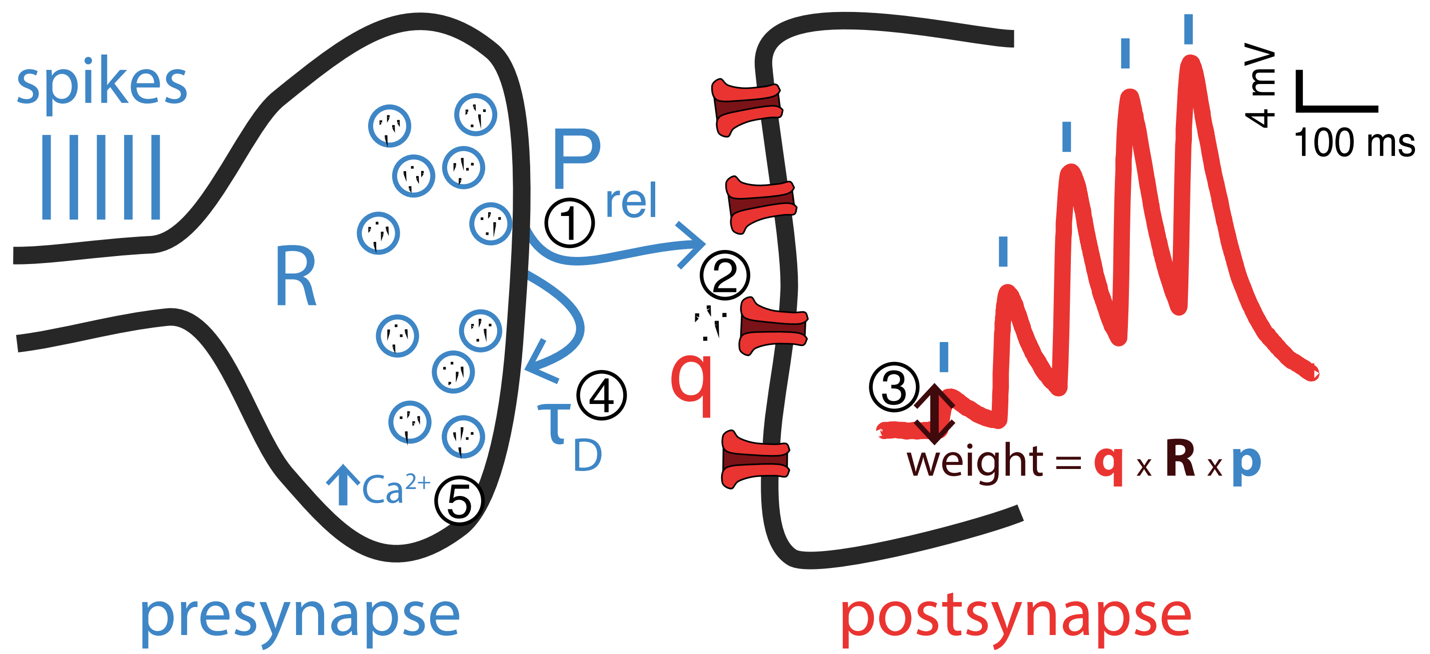


Baddeley, Nature Rev Neurosci 2003

Lets play block 'tapping'



Short-term facilitation as a theory of working memory



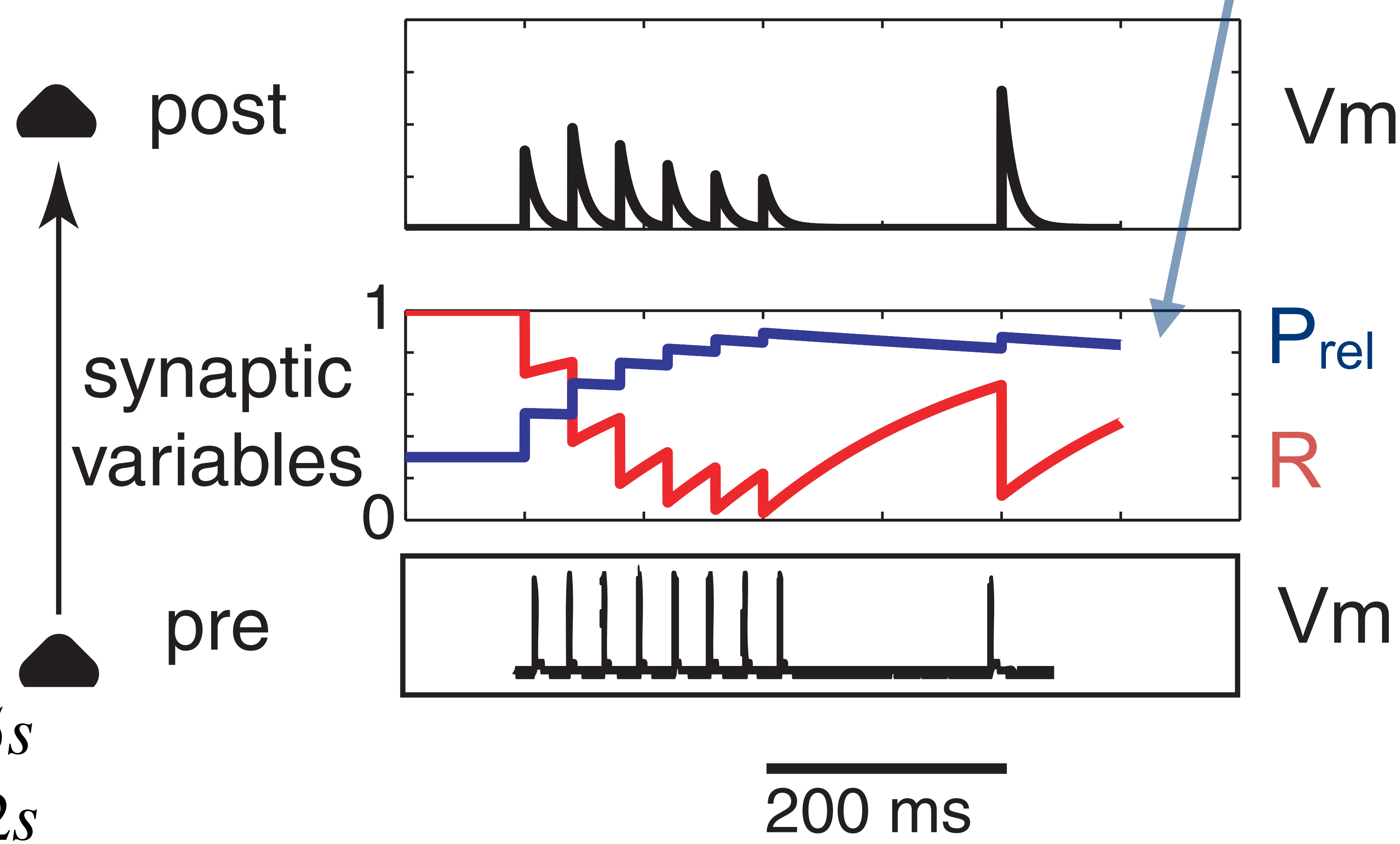
Key idea: Use slow decay in the release probability dynamics *p* to remember previous inputs.

$$\frac{dR}{dt} = \frac{1-R}{\tau_D} - Rp\delta_{\text{spike}} \qquad \frac{dp}{dt} = \frac{P_r - p}{\tau_F} + (1-p)\delta_{\text{spike}}$$

$$\tau_F \gg \tau_D$$

Short-term facilitation
as a synaptic theory of working memory

Here STF is used as a model for working memory, where the dynamics of Prel are a memory trace of previous input activity.



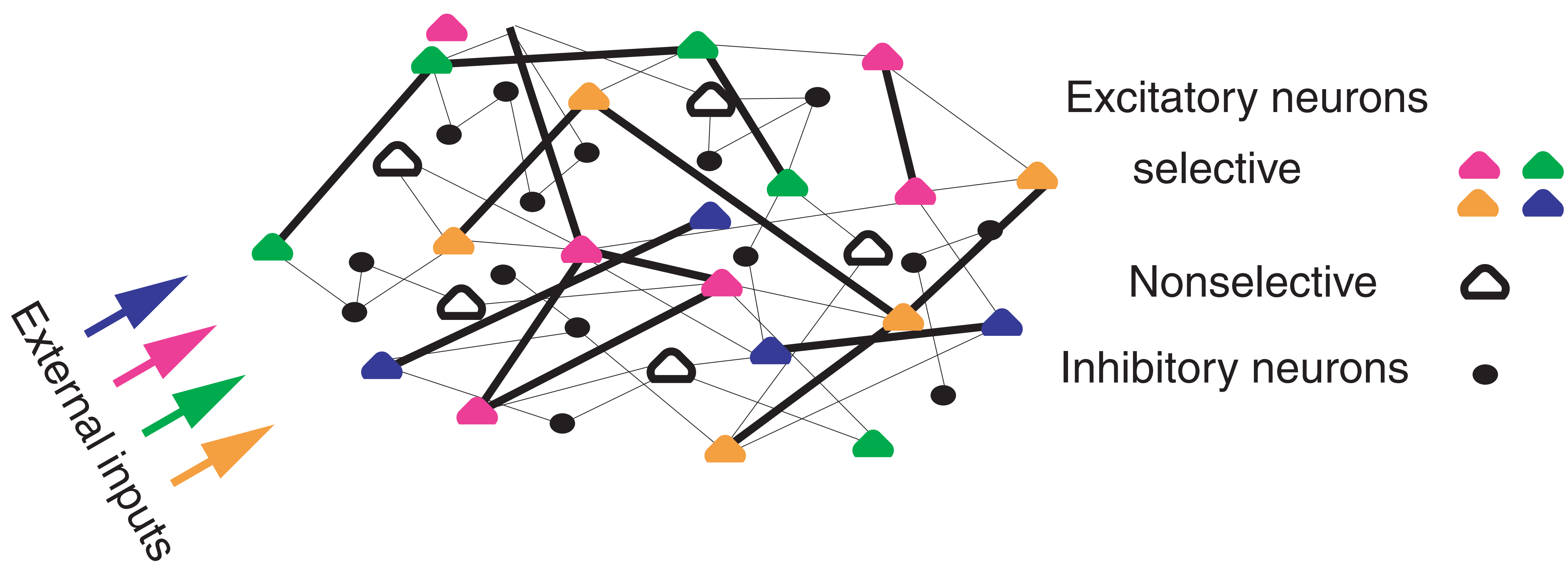
$\tau_F = 1.5s$

$\tau_D = 0.2s$

Mongillo et al. Science 2008

Short-term facilitation as a synaptic theory of working memory

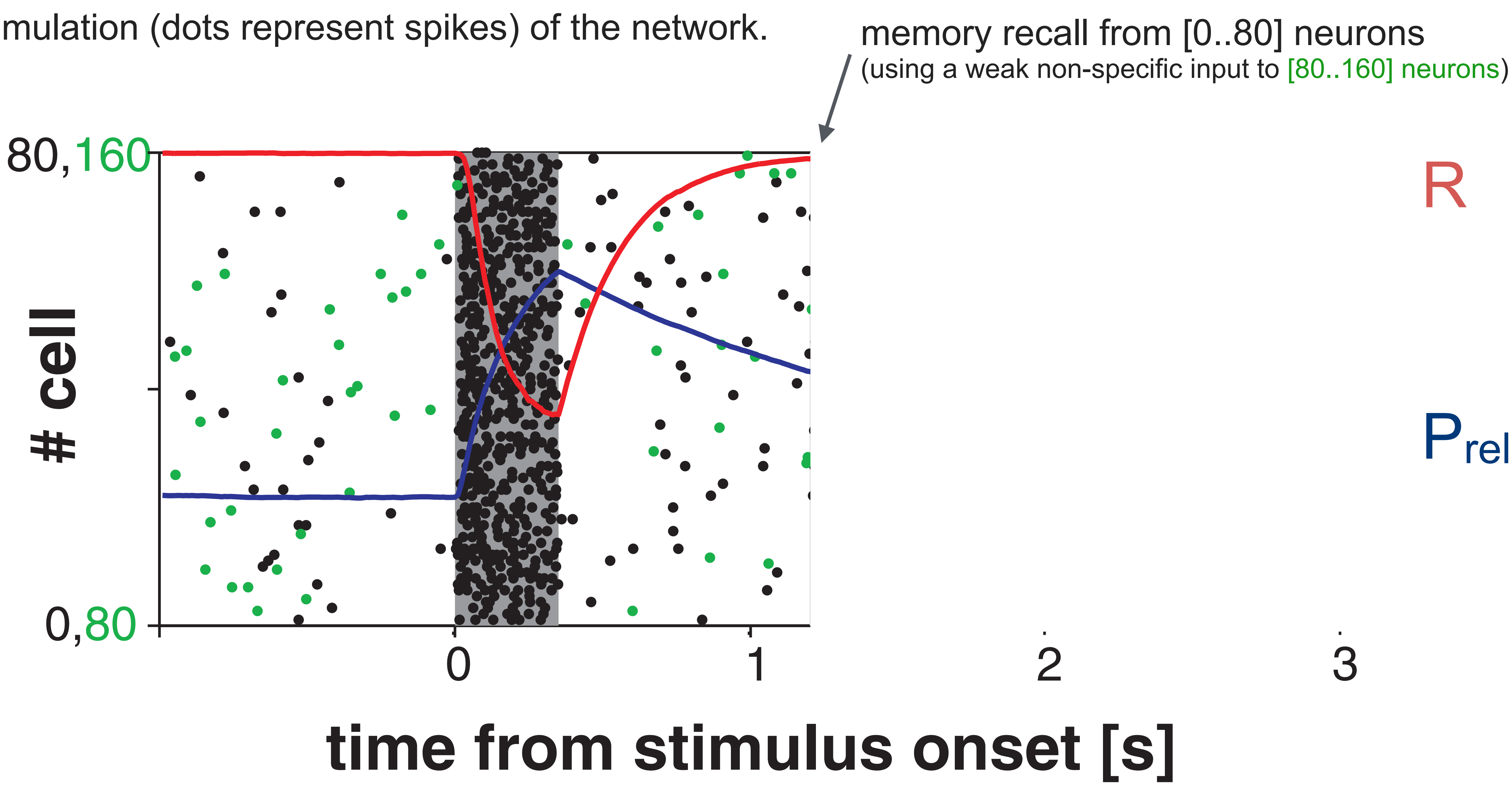
A recurrent neural network of integrate and fire neurons was used to demonstrate the idea.



Mongillo et al. Science 2008

Short-term facilitation as a synaptic theory of working memory

A simulation (dots represent spikes) of the network.



Mongillo et al. Science 2008

Short-term facilitation
as a synaptic theory of working memory

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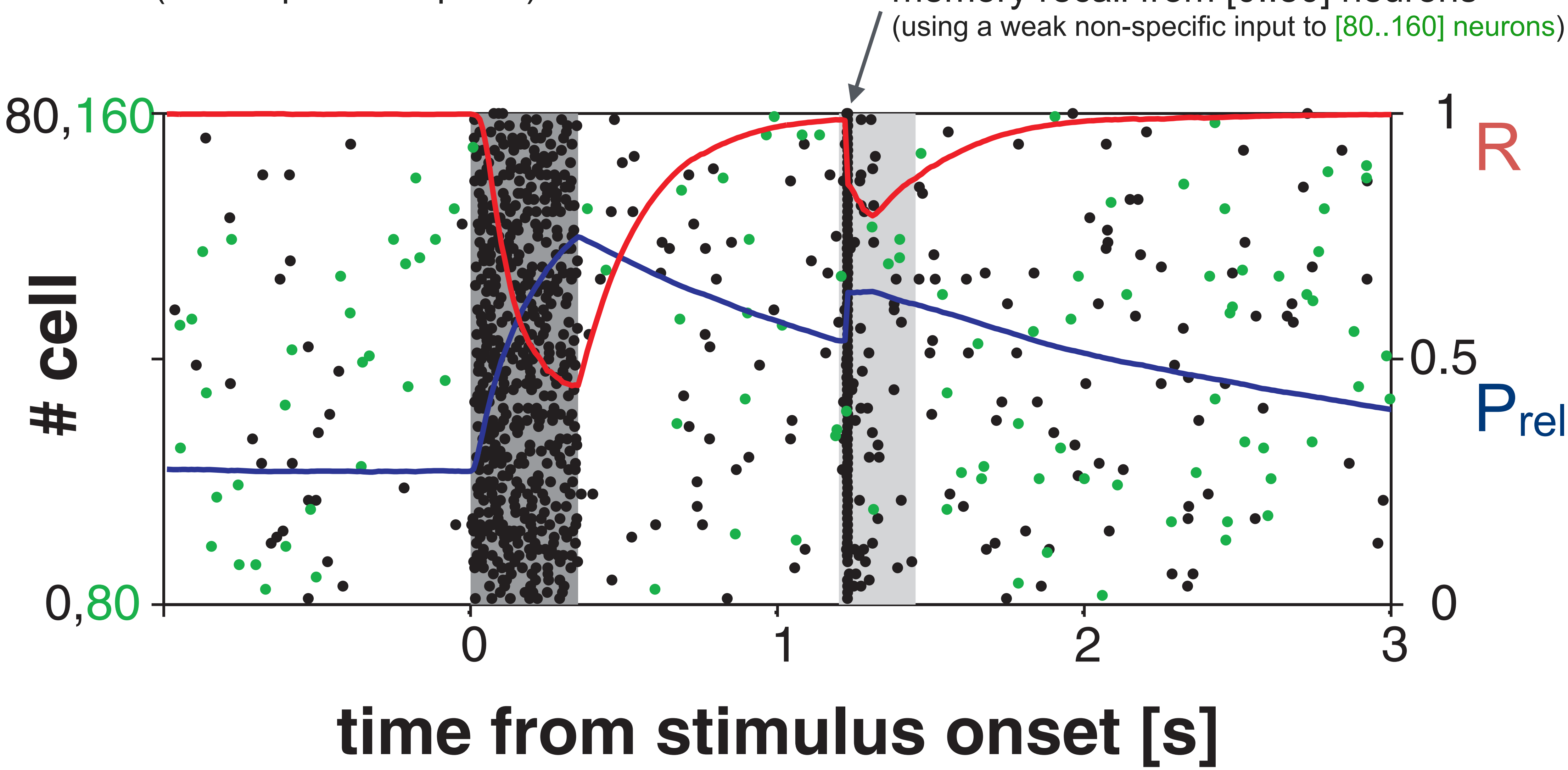
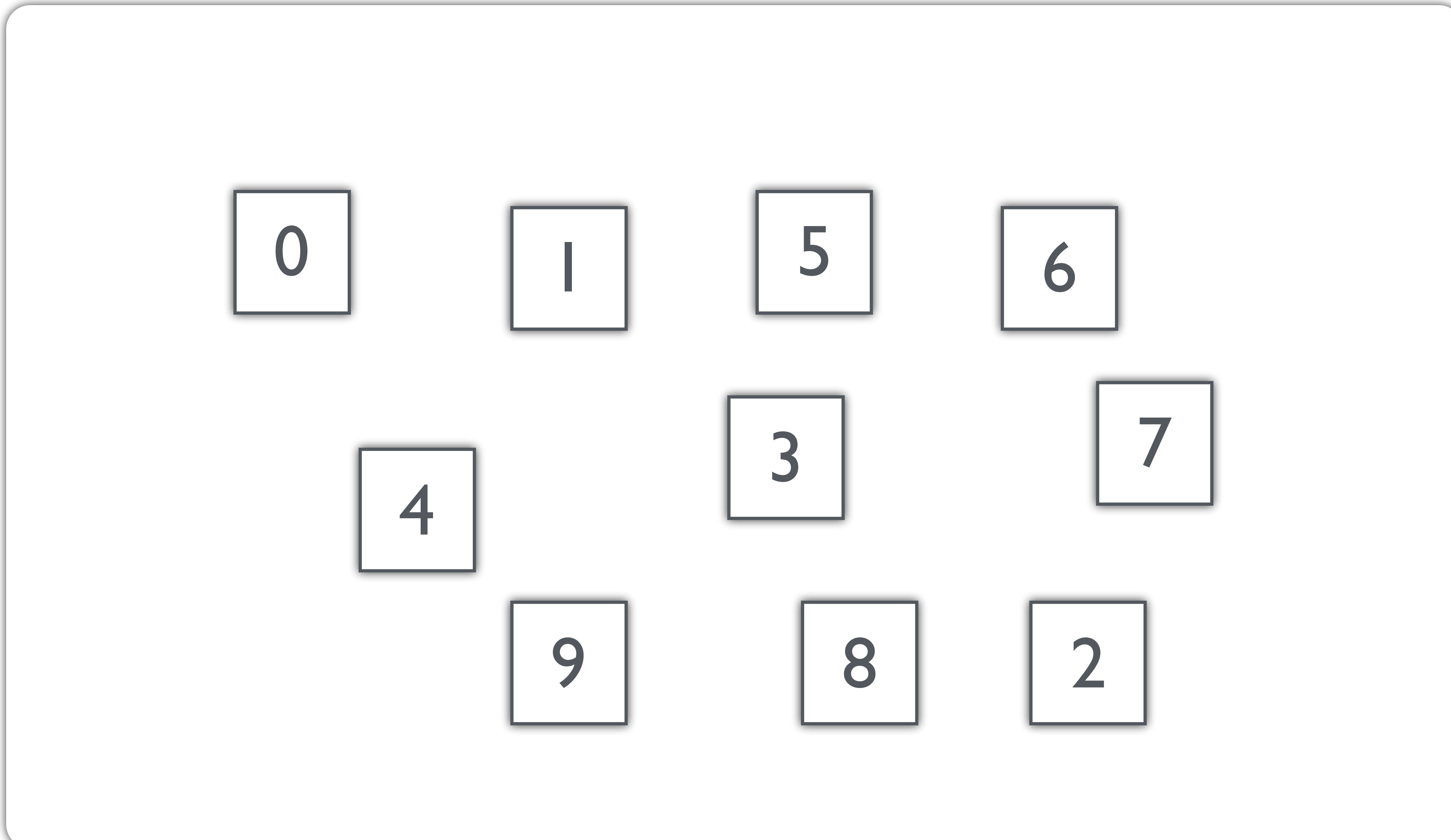


Note: This suggests that every one of the **1000 trillion synapses** in our brains has some form of working memory, and therefore contribute to reasoning!

Mongillo et al. Science 2008

Can you recall the number?



Summary: short-term plasticity (part 2)

1. STD is important to *control network activity*, helping to prevent pathological states

2. STF has been proposed a new (exciting) theory of how we hold items in memory for short periods of time (working memory)

Questions?

References

Text books:

General biology: Wikipedia/Principles of neuroscience [neuroscience bible]

Computational Neuroscience: Neuronal Dynamics by Gerstner, Kistler, Naud and Paninski

Computational Neuroscience: Principles of Computational Modelling in Neuroscience by Sterratt, Gillies, Graham and Willshaw

[Chapter on Synaptic modelling: http://dai.fmph.uniba.sk/courses/comp-neuro/reading/Sterratt_CH7_synapse.pdf]

And the papers referred to during the lecture.