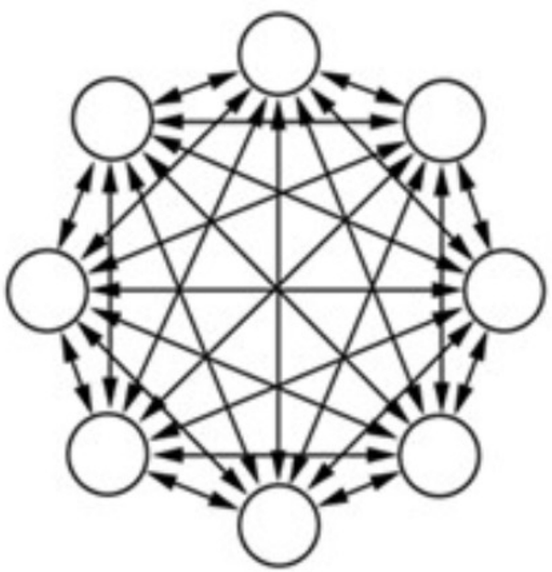
Short-term Plasticity (STP)
&
Working Memory

刘潇
2021.08.13

Short-term Plasticity (STP)

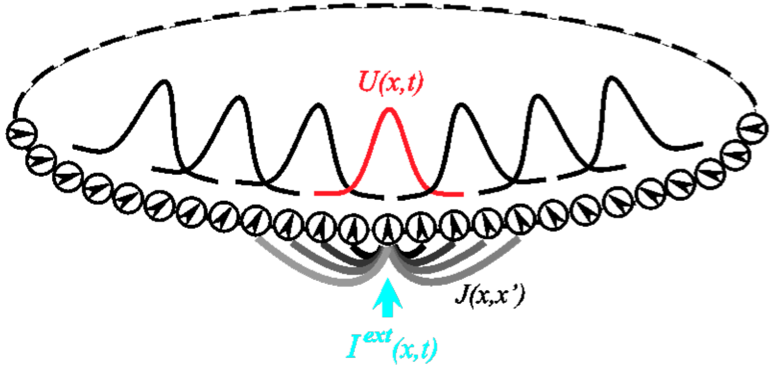
Synapse & Connection

Hopfield Network

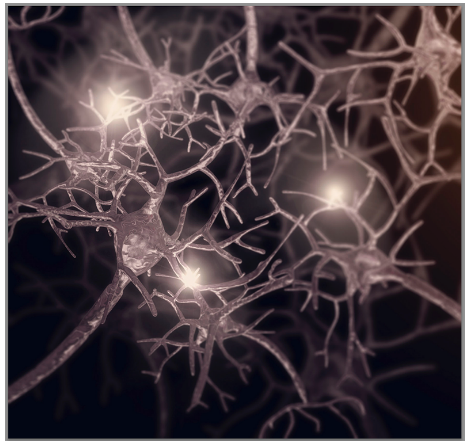


$$w_{i,j} = \begin{cases} \frac{1}{P}\sum_{\mu=1}^{P} \xi_i^\mu \xi_j^\mu, & i \neq j; \\ 0, & i = j. \end{cases}$$

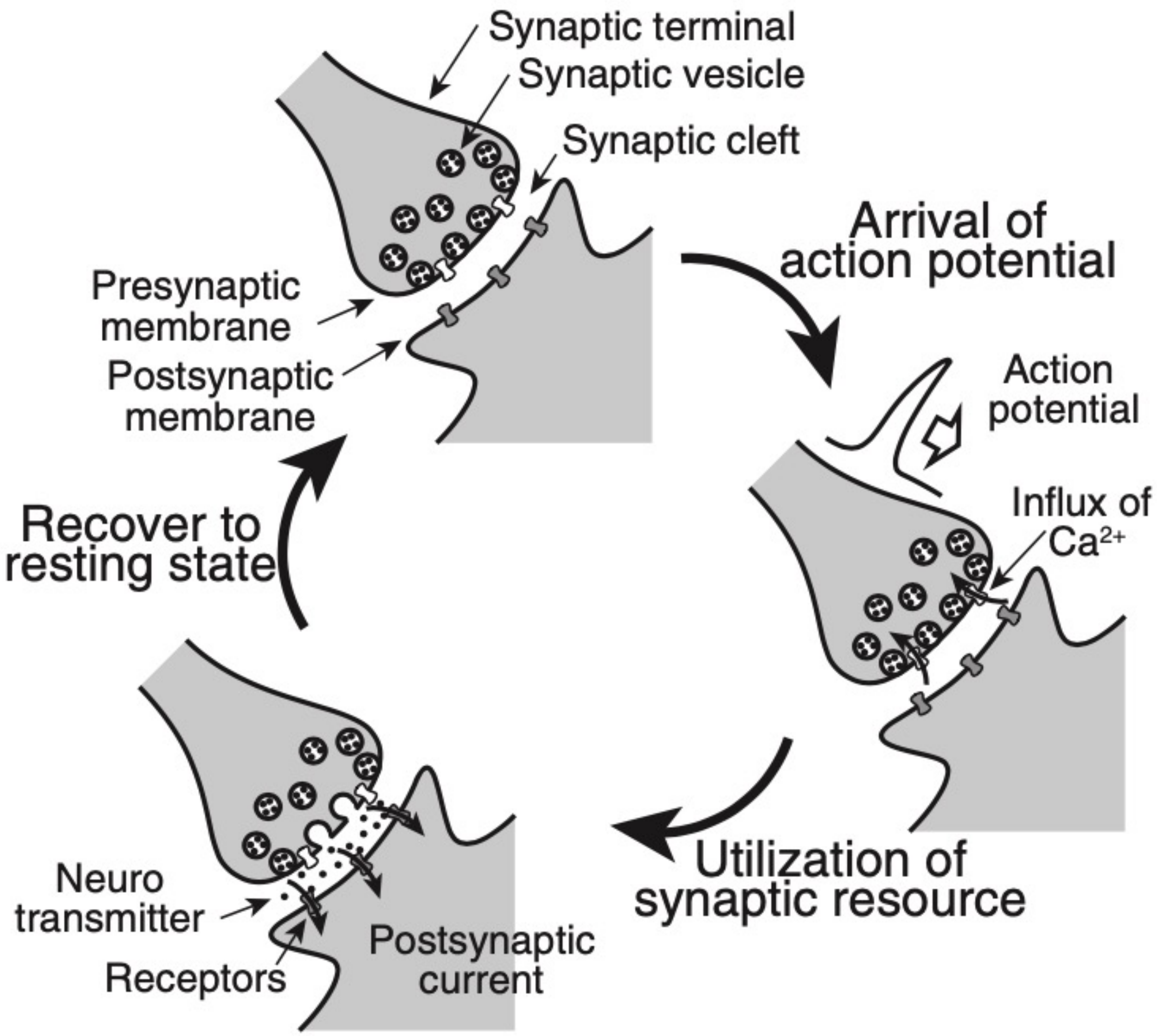
CANN

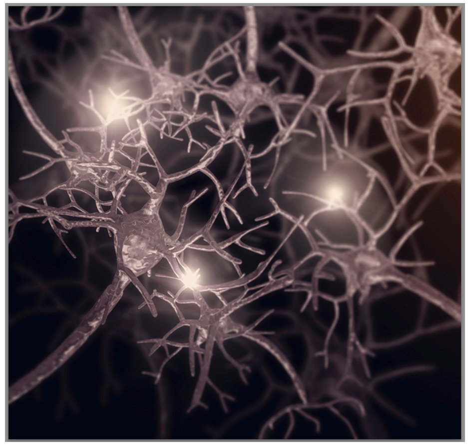


$$J(x - x') = \frac{J}{\sqrt{2\pi a}} \exp\left[-\frac{(x - x')^2}{2a^2}\right]$$

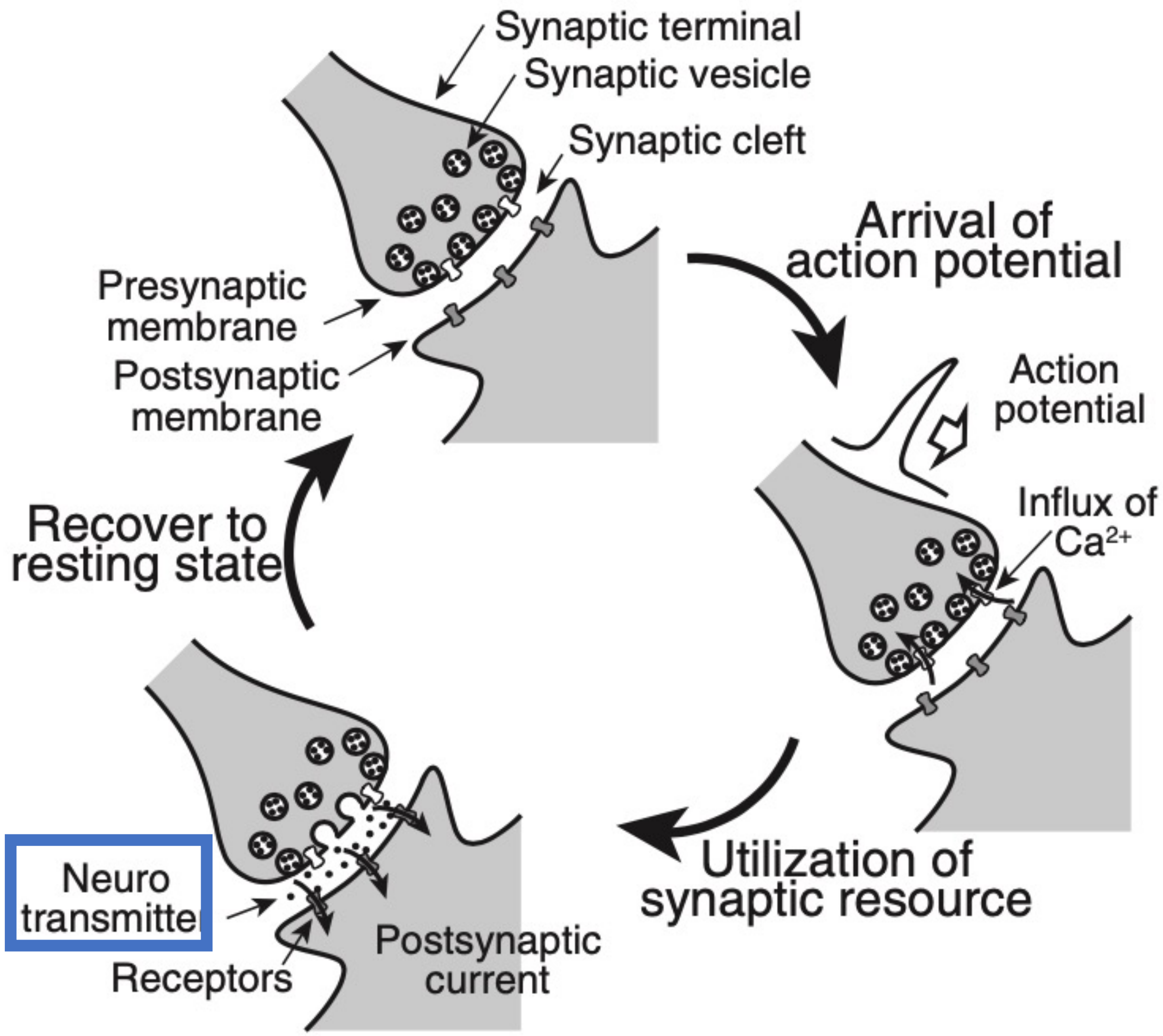


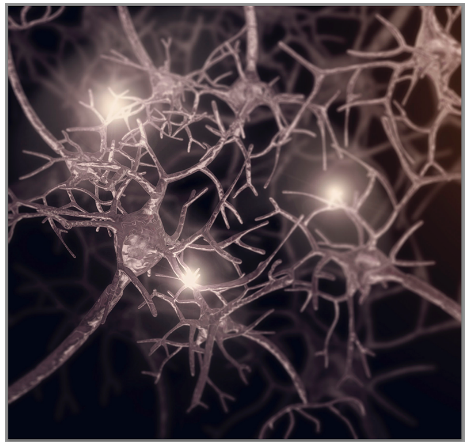
Synaptic Transmission

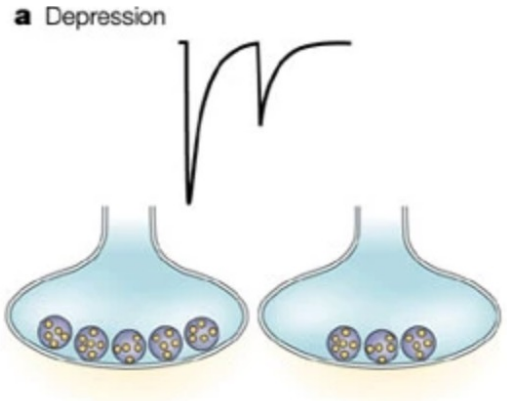




Synaptic Mechanisms







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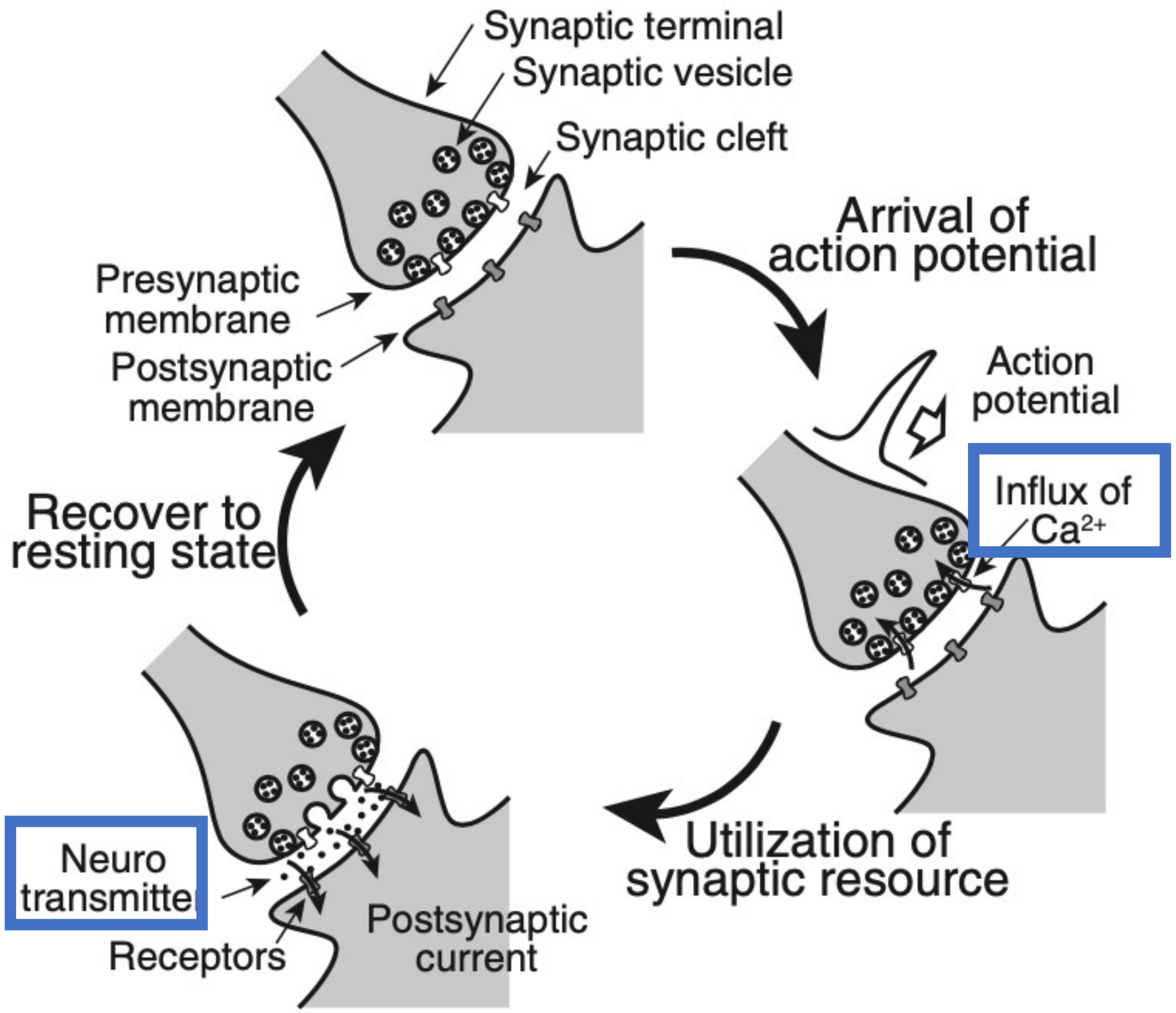
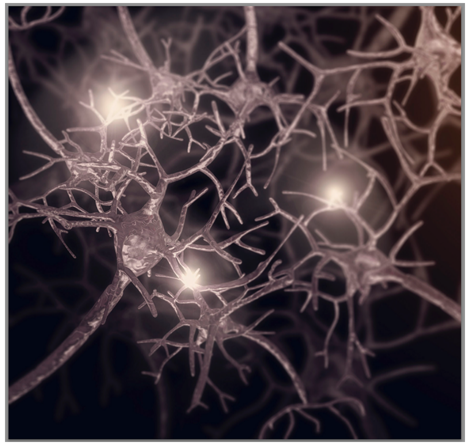
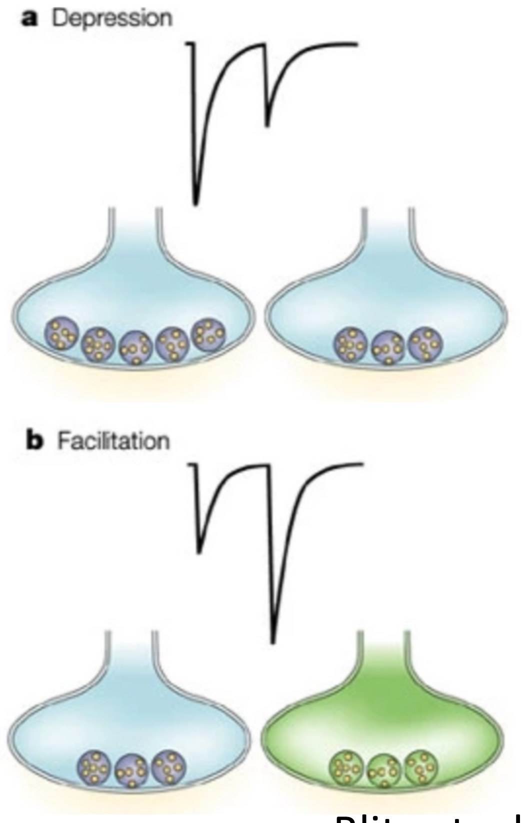
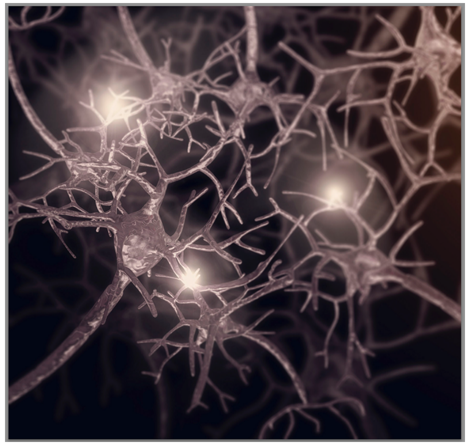






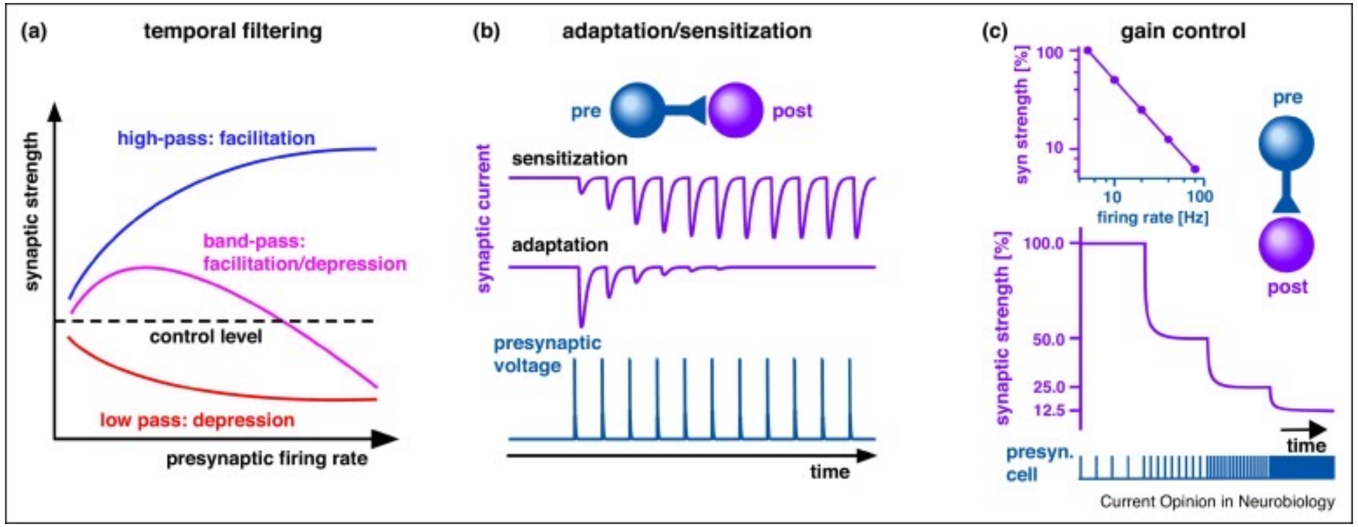
Blitz et. al 2004

Synaptic Short Term Plasticity(STP)

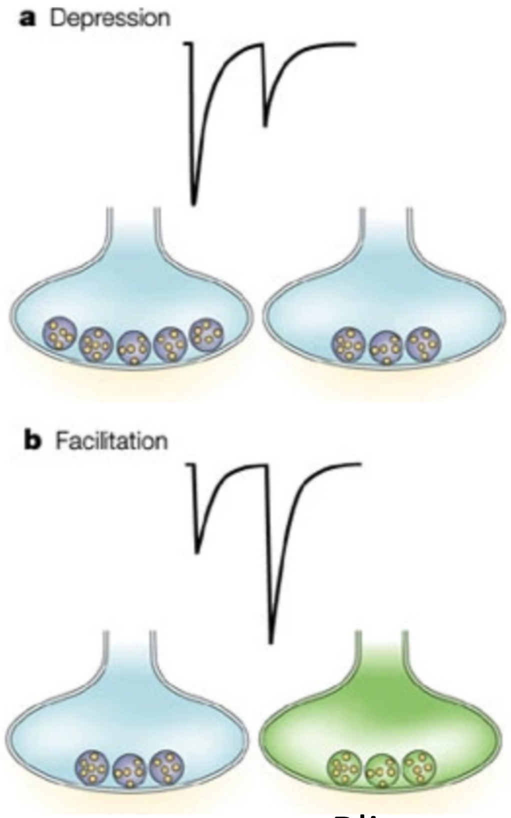


The short-term changes in the efficacy of synaptic transmission occur with the consecutive activation of presynaptic neurons (B.Gutkin, et al., 2001, H. Markram and M. Tsodyks, 1996, Tsodyks et al., 1998).

- sub-second timescale
- last for at most a few minutes
- response properties of synapses
- different functional roles

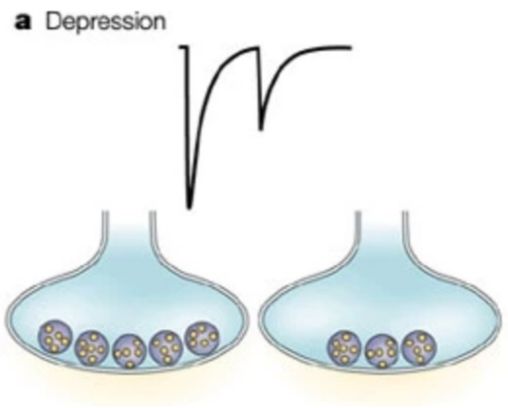


Anwar et. al 2017



Blitz et. al 2004

Synaptic Short Term Plasticity(STP)



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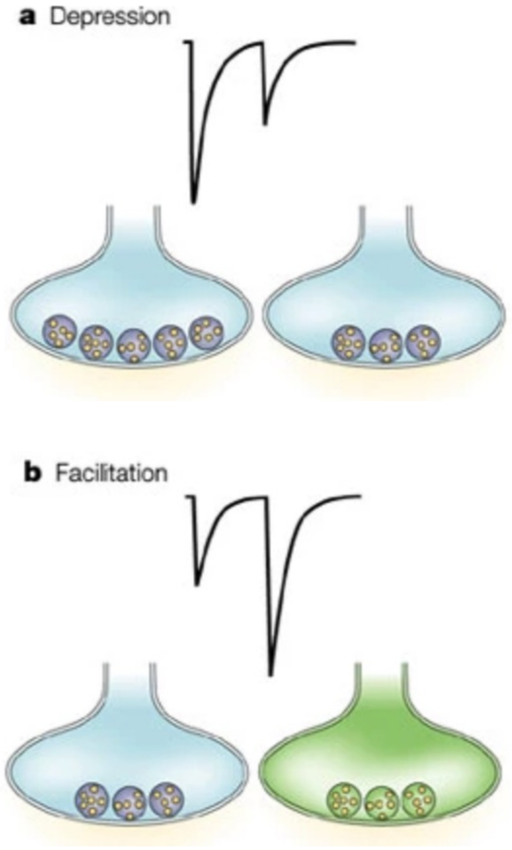
  Influx of calcium into the axon terminal after spike generation, which increases the release probability of neurotransmitters.



Blitz et. al 2004

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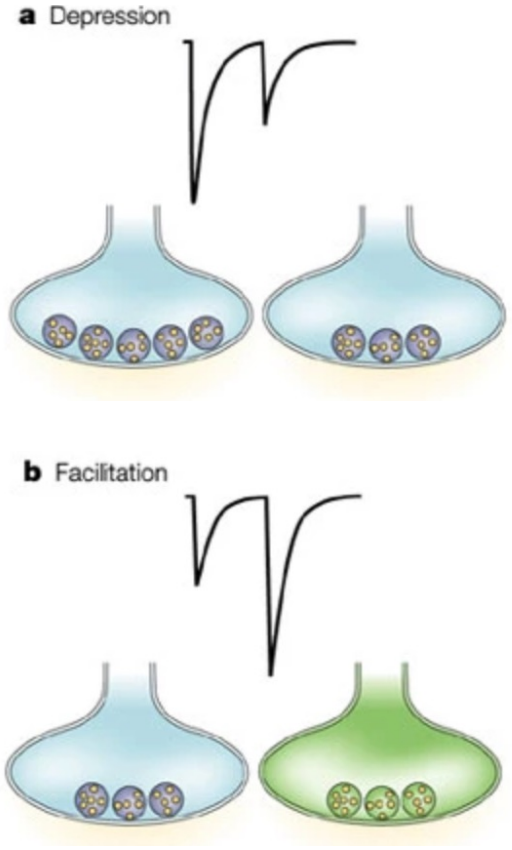
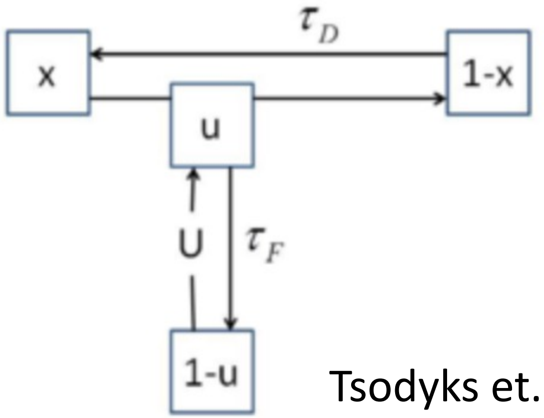


Blitz et. al 2004



Tsodyks et. al 1998

x $(0 \leq x \leq 1)$, denoting the fraction of resources that remain available after neurotransmitter depletion.

u $(0 \leq u \leq 1)$, representing the fraction of available resources ready for use (release probability)

U is the increment of u produced by a spike

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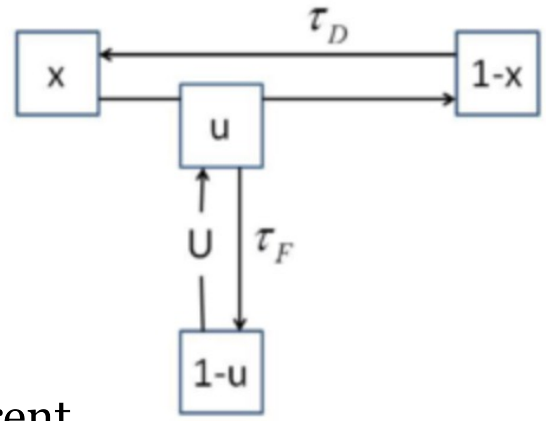
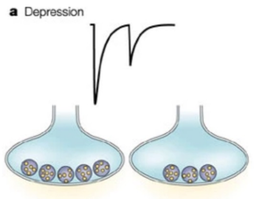


- STD (short-term synaptic depression)

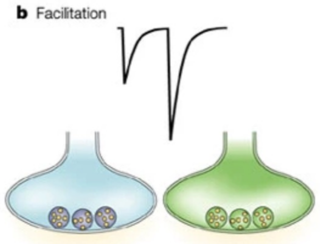
  A transient decrease in the amount of releasable neurotransmitters x.



$$\frac{dx}{dt} = \frac{1-x}{\tau_d} - u^{+}x^{-}\delta(t-t_{sp})$$

- STF (short-term synaptic facilitation)

  An increase in the calcium concentration in synaptic terminals.



$$\frac{du}{dt} = -\frac{u}{\tau_f} + U(1-u^{-})\delta(t-t_{sp})$$

$$u^{+} = u^{-} + U(1-u^{-})$$

- Post-synaptic current

$$\frac{dI}{dt} = -\frac{I}{\tau_s} + Au^{+}x^{-}\delta(t-t_{sp})$$

x $(0 \le x \le 1)$, denoting the fraction of resources that remain available after neurotransmitter depletion.

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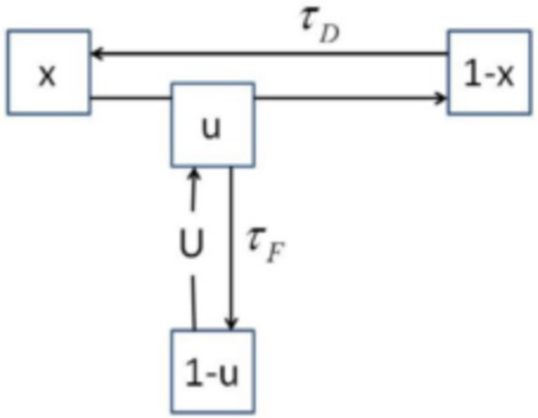
U is the increment of u produced by a spike

STP in BrainPy

- STP with LIF neurons

```
class LIF(bp.NeuGroup):
  target_backend = ['numpy', 'numba']

  @staticmethod
  @bp.odeint(method='exponential_euler')
  def integral(V, t, Iext, V_rest, R, tau):
    dvdt = (-V + V_rest + R * Iext) / tau
    return dvdt

  def __init__(self, size, t_ref=1., V_rest=0., V_reset=0.,
               V_th=20., R=1., tau=10., **kwargs):
    super(LIF, self).__init__(size=size, **kwargs)
```



$$\frac{du}{dt} = -\frac{u}{\tau_f} + U(1-u^-)\delta(t-t_{sp})$$

$$\frac{dx}{dt} = \frac{1-x}{\tau_d} - u^+x^-\delta(t-t_{sp})$$

$$\frac{dI}{dt} = -\frac{I}{\tau_s} + Au^+x^-\delta(t-t_{sp})$$

$$u^+ = u^- + U(1-u^-)$$

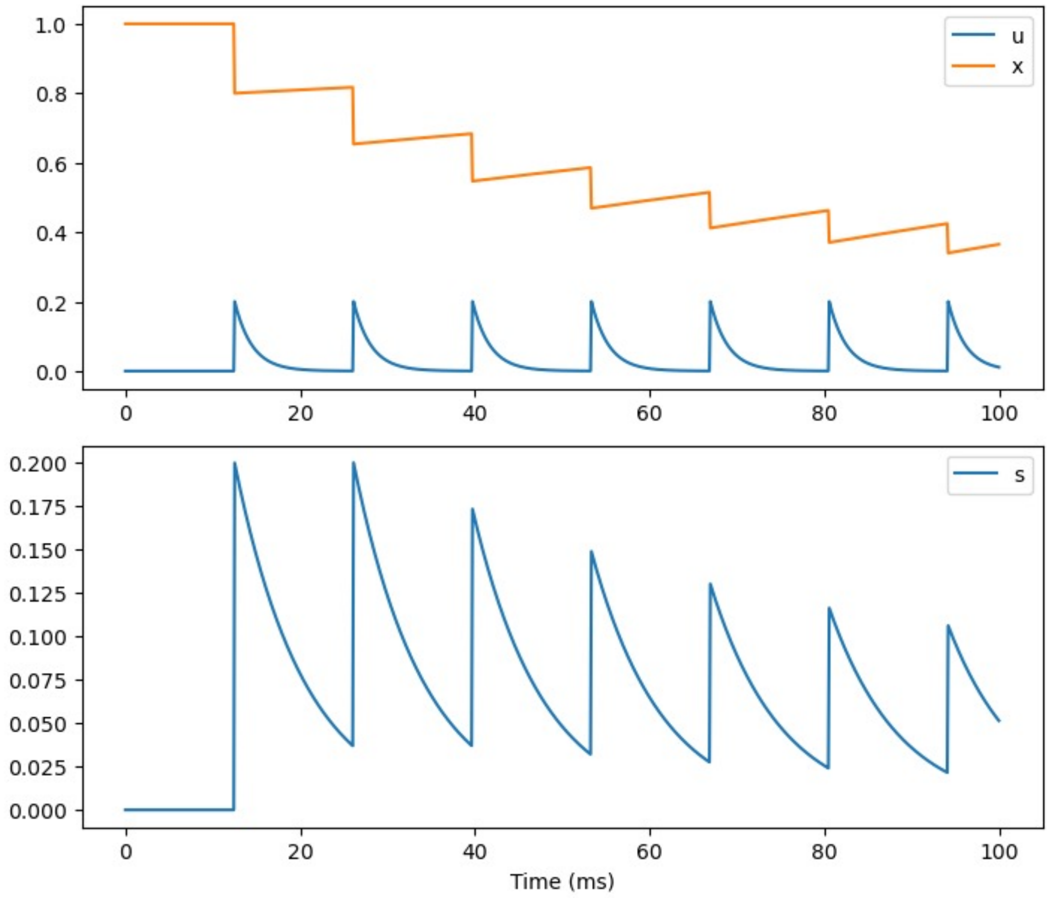
$$\boxed{\begin{aligned}\frac{du}{dt} &= -\frac{u}{\tau_f}\\ \frac{dx}{dt} &= \frac{1-x}{\tau_d}\\ \frac{dI}{dt} &= -\frac{I}{\tau}\end{aligned}}$$

$$\text{if (pre fire), then } \begin{cases} u^+ = u^- + U(1-u^-) \\ I^+ = I^- + Au^+x^- \\ x^+ = x^- - u^+x^- \end{cases}$$

```
class STP(bp.TwoEndConn):
    target_backend = 'general'

    @staticmethod
    @bp.odeint(method='exponential_euler')
    def integral(s, u, x, t, tau, tau_d, tau_f):
        dsdt = -s / tau
        dudt = - u / tau_f
        dxdt = (1 - x) / tau_d
        return dsdt, dudt, dxdt
```

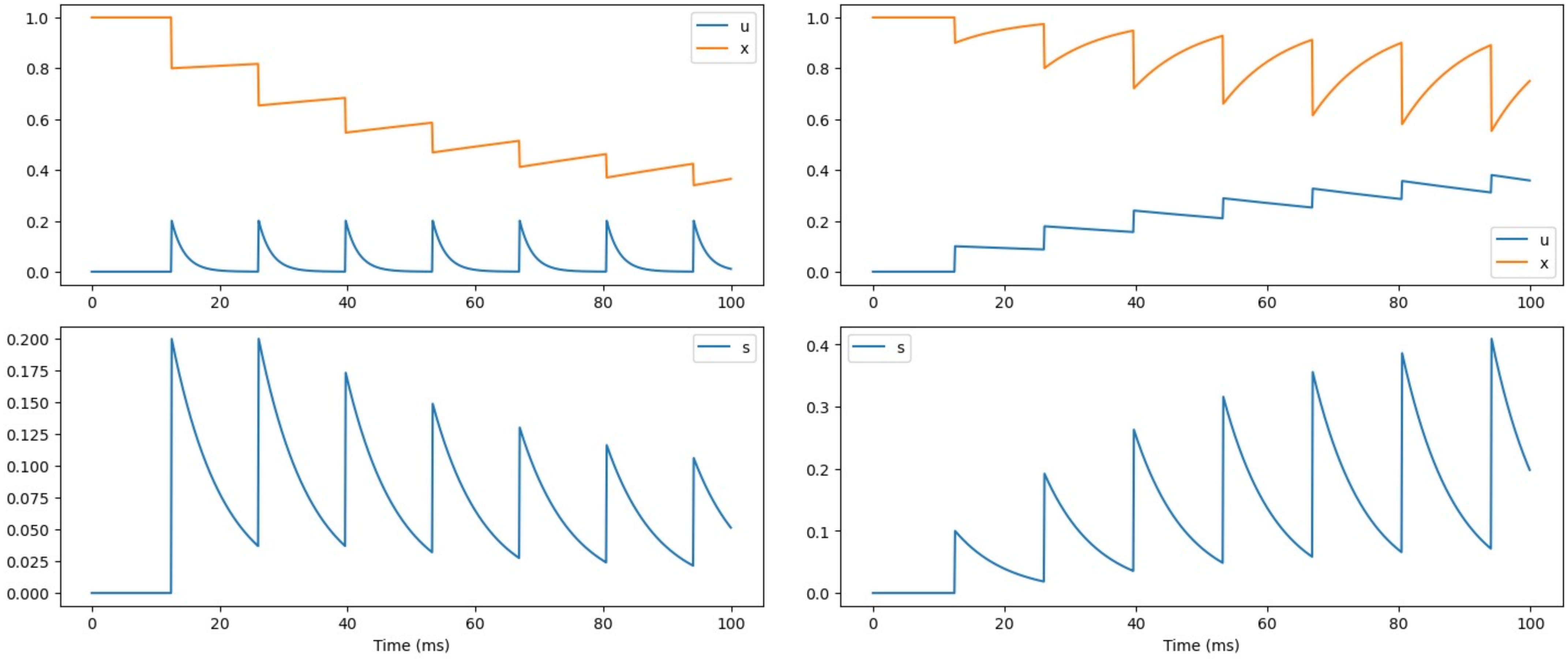
```
def update(self, _t):
    for i in range(self.num):
        pre_id, post_id = self.pre_ids[i], self.post_ids[i]

        self.s[i], u, x = self.integral(self.s[i], self.u[i], self.x[i], _t, self.tau, self.tau_d, self.tau_f)
        if self.pre.spike[pre_id]:
            u += self.U * (1 - self.u[i])
            self.s[i] += self.A * u * self.x[i]
            x -= u * self.x[i]
        self.u[i] = u
        self.x[i] = x

        # output
        self.I_syn.push(i, self.s[i])
        self.post.input[post_id] += self.I_syn.pull(i)
```

STP in BrainPy



tau_d=150., tau_f=2.

STP in BrainPy

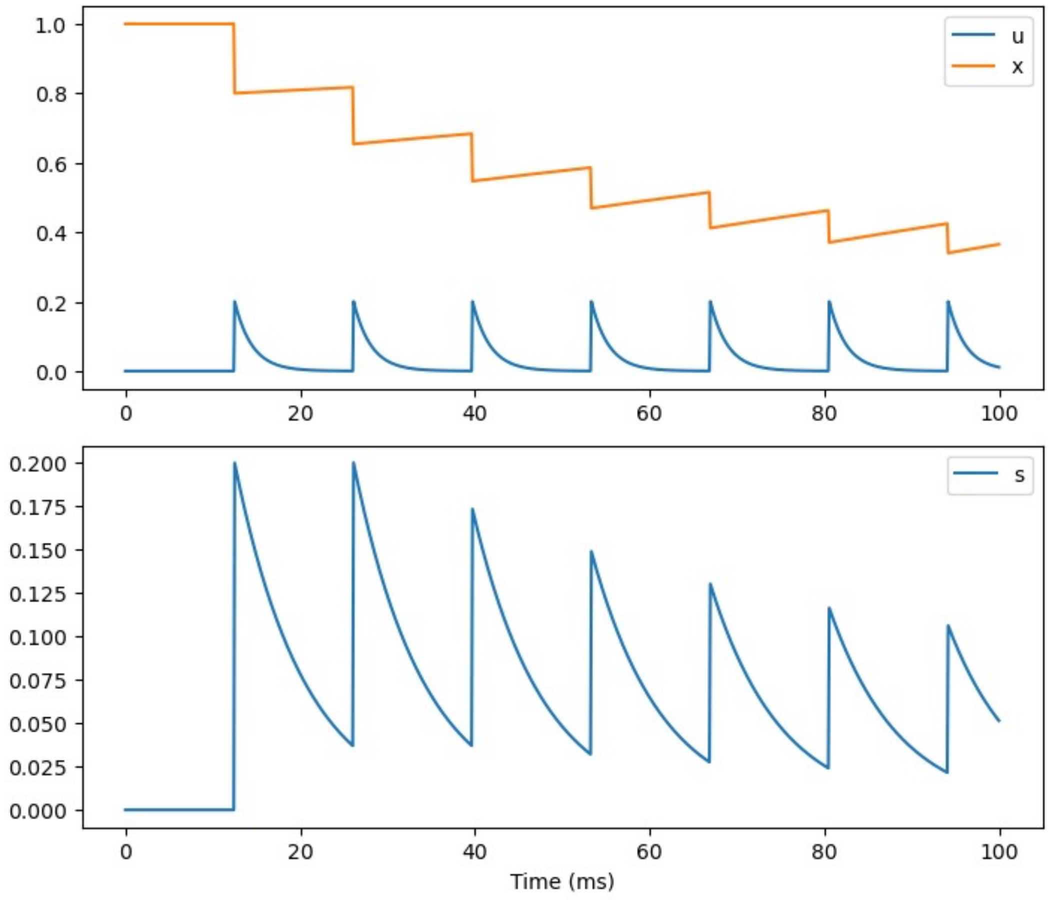


tau_d=150., tau_f=2.

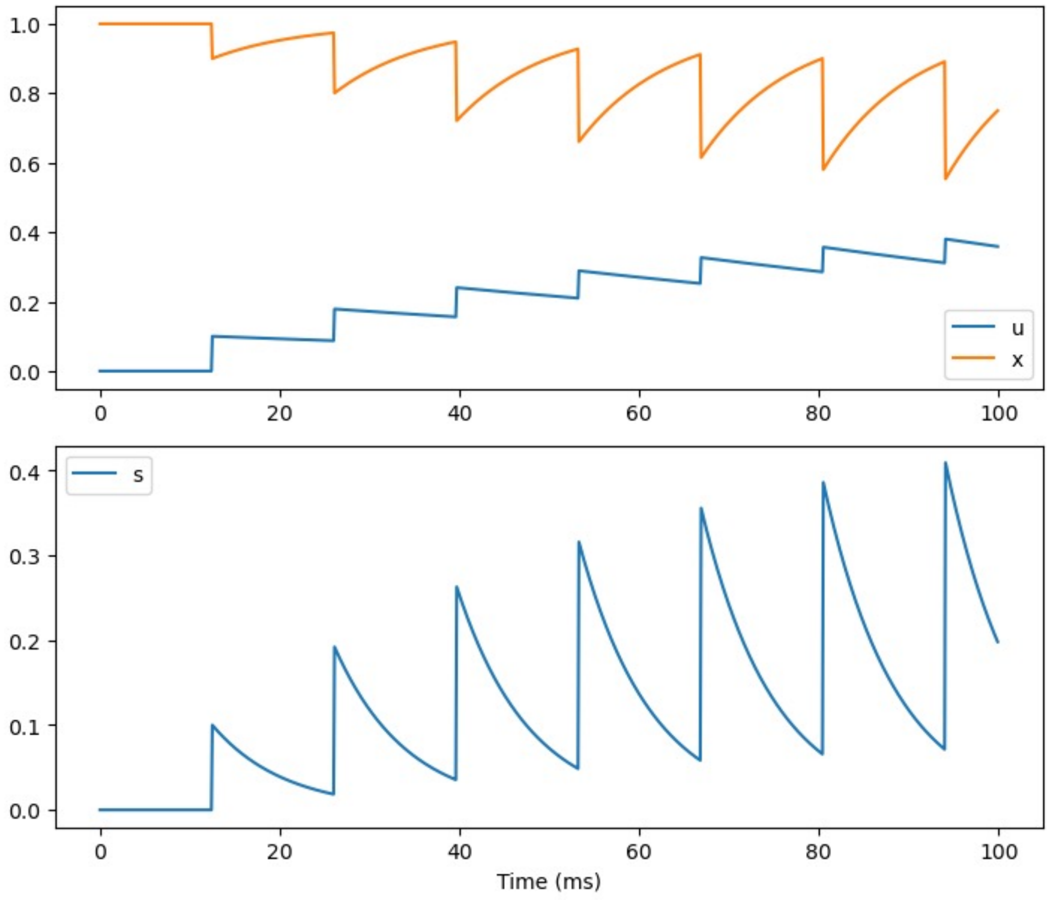
tau_d=10, tau_f=100.

STP in BrainPy

Try more?



tau_d=150., tau_f=2.



tau_d=10, tau_f=100.

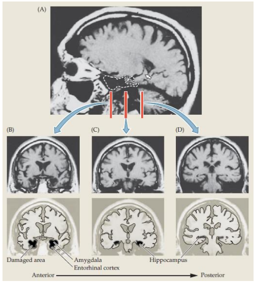
Working Memory

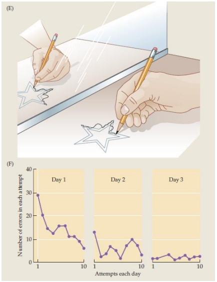
Memory Systems?

H.M. patient: purity of memory deficit

- H.M. was widely studied from late 1957 until his death in 2008
- Little difficulty in other cognitive domains (normal sensory and perceptual functions, normal IQ, no deficit in executive tasks)
- Memory deficits are generalized to all kinds of information and sensory modalities (verbal, nonverbal, different sensory modalities)
- Intact working memory (e.g., digit-span task)
- Limited to declarative memory (facts and events), but not for nondeclarative memory (performance; e.g., motor, cognitive skills; mirror drawing task), although he did not consciously remember having learned this before. (most importantly!)

H.M. patient

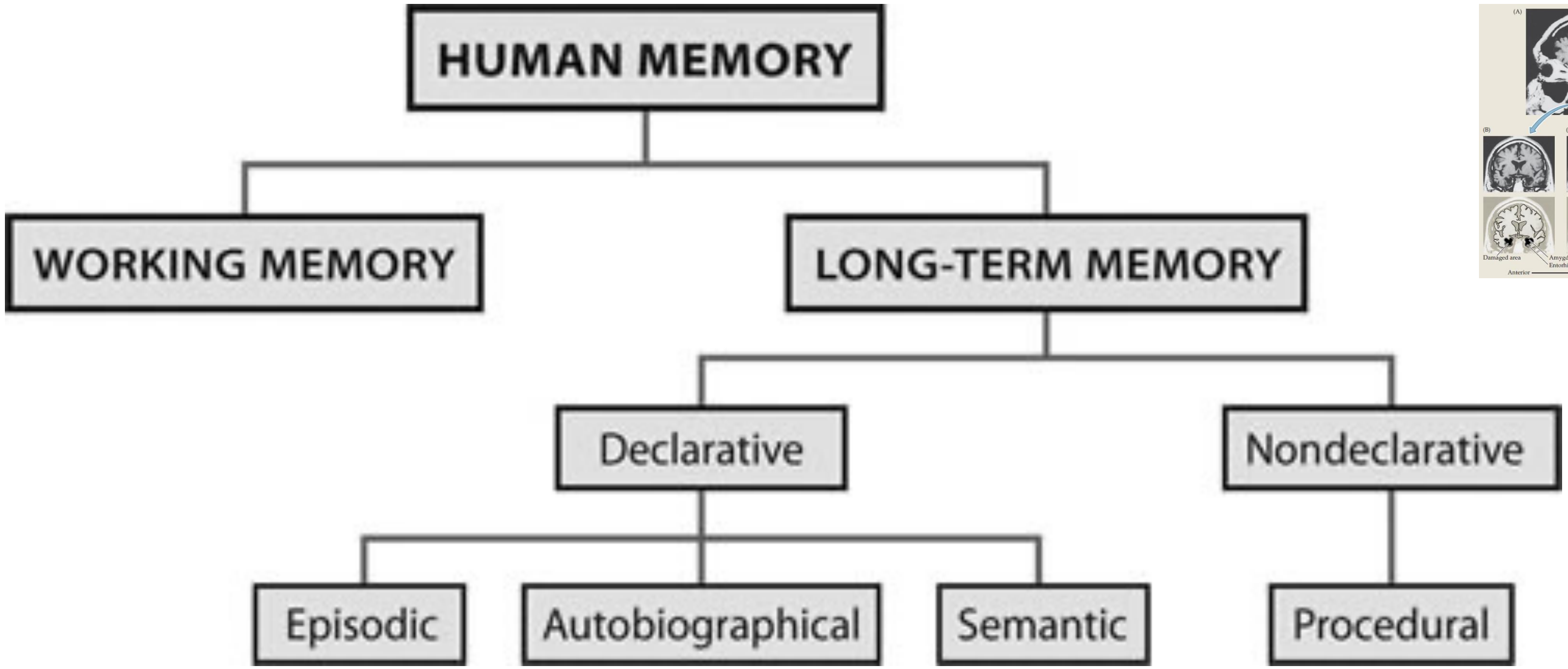


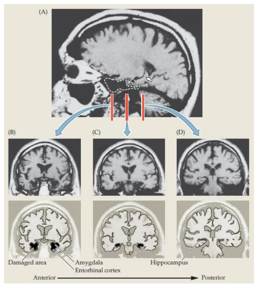


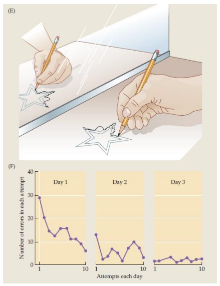
Scovile & Milner,

A general taxonomy of memory systems

H.M. patient





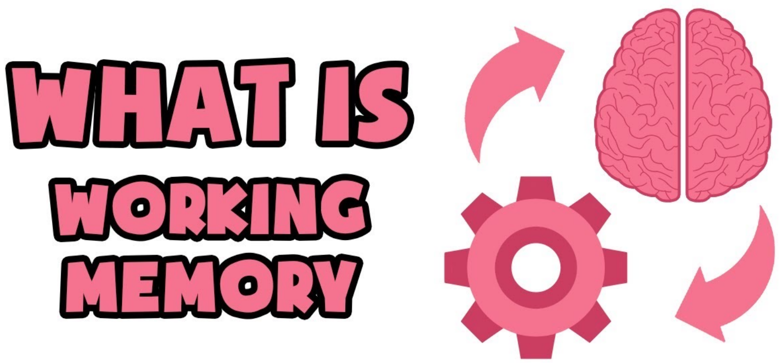


Working Memory

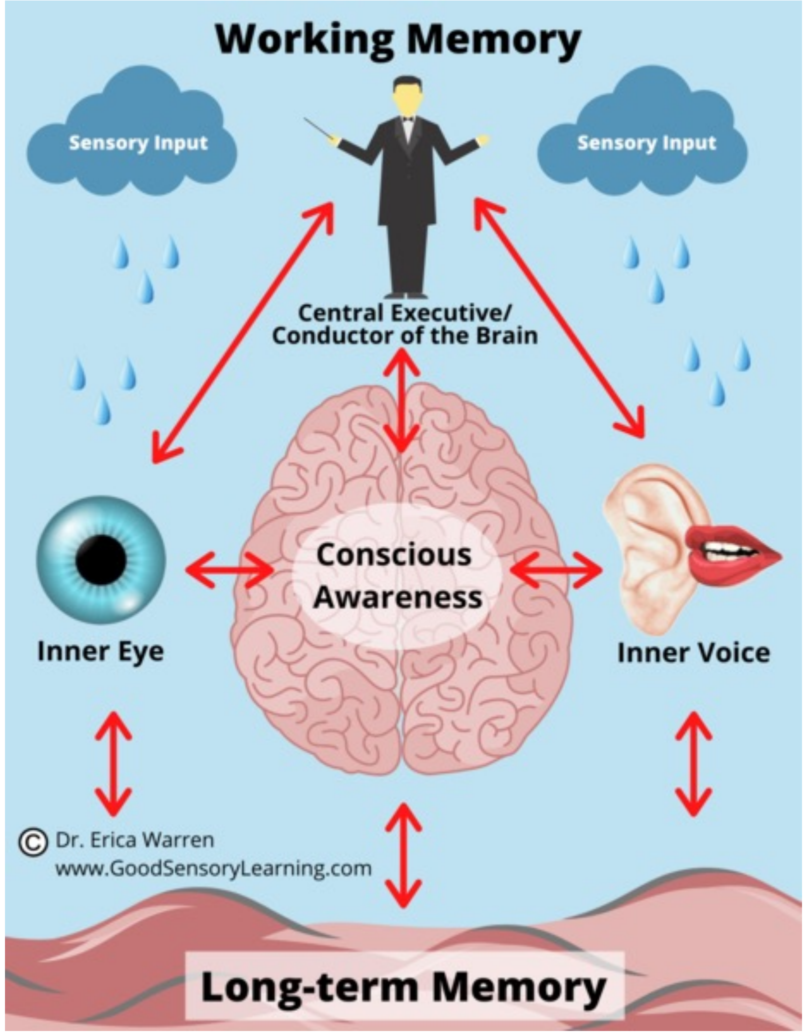
- Working memory is a **limited capacity** part of the human memory system that combines the **temporary storage** and **manipulation of information** in the service of cognition.

Miller et al., 1960, Baddeley and Hitch, 1974, Baddeley, 2003

- Working memory is widely thought to be one of the most important mental faculties, critical for cognitive abilities such as planning, problem-solving, and reasoning and it is often included among executive functions.
- Concept in cognition, neuropsychology, normal and abnormal child development and neuroimaging.

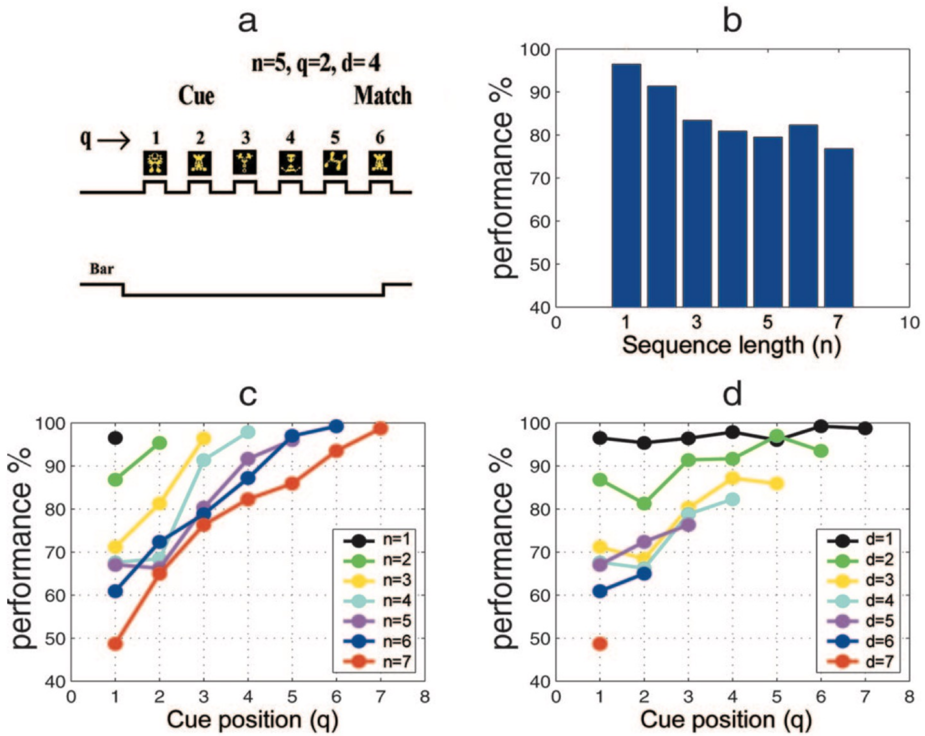


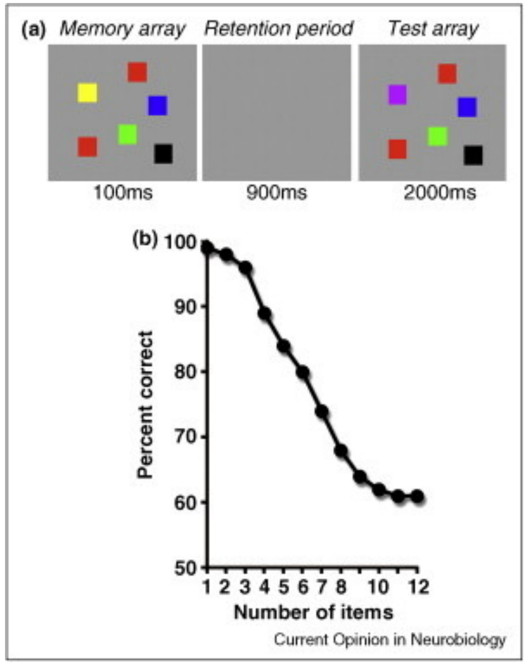
WM & Short-term memory

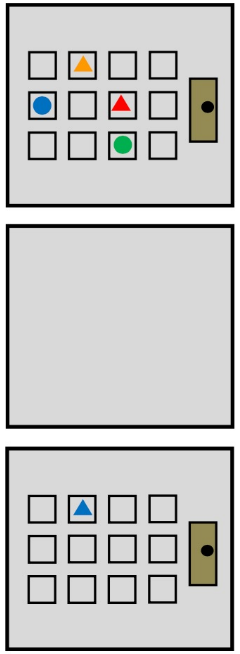


Limited Capacity

Magical Numbe







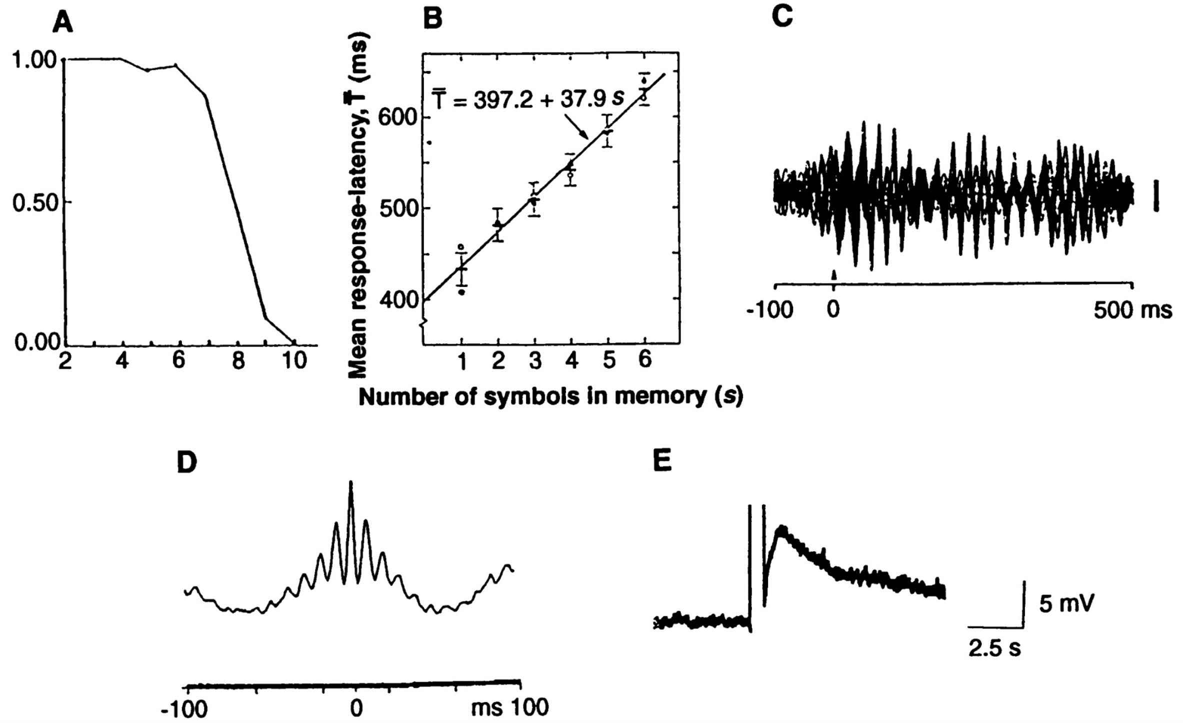
Dual-shape
0.5 second

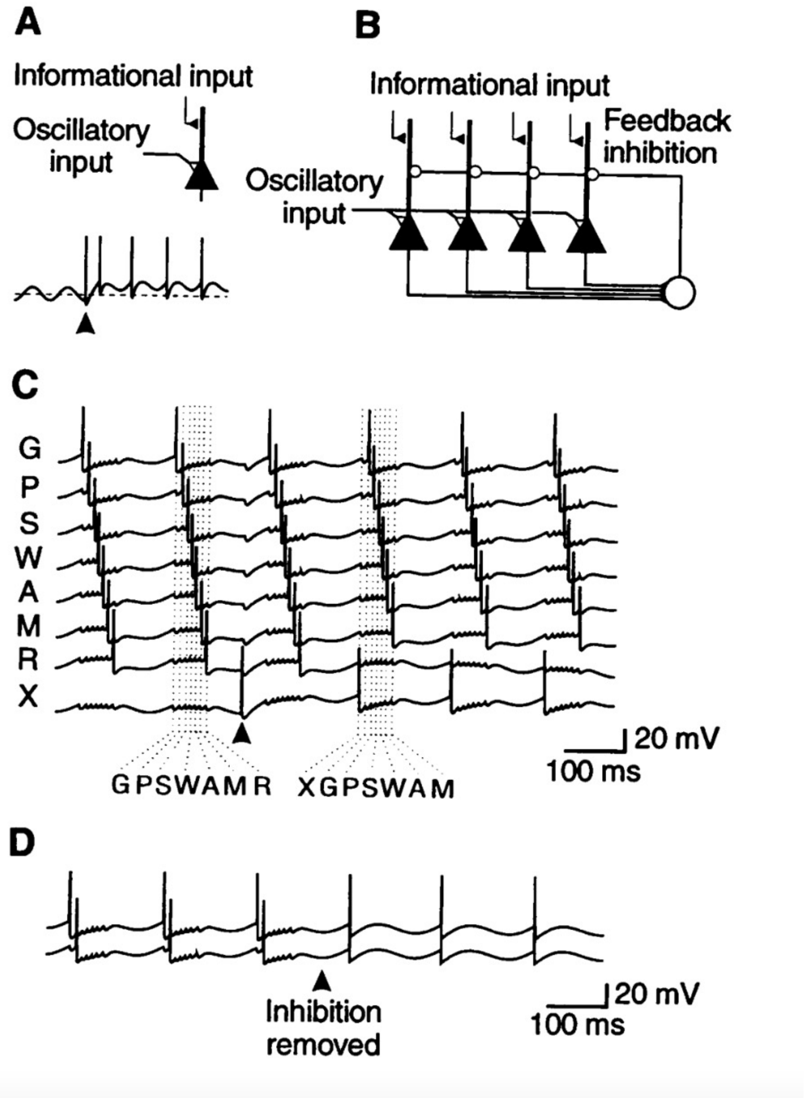
Added time to think. 1.5 seconds.

Test item. Indicate where the item belongs.
If it is a new item, select the door icon.
That is the answer here because there was
no blue triangle in the memory array.

Amit et al., 2003, Rolls et al., 2013

Why Magical Number 7?



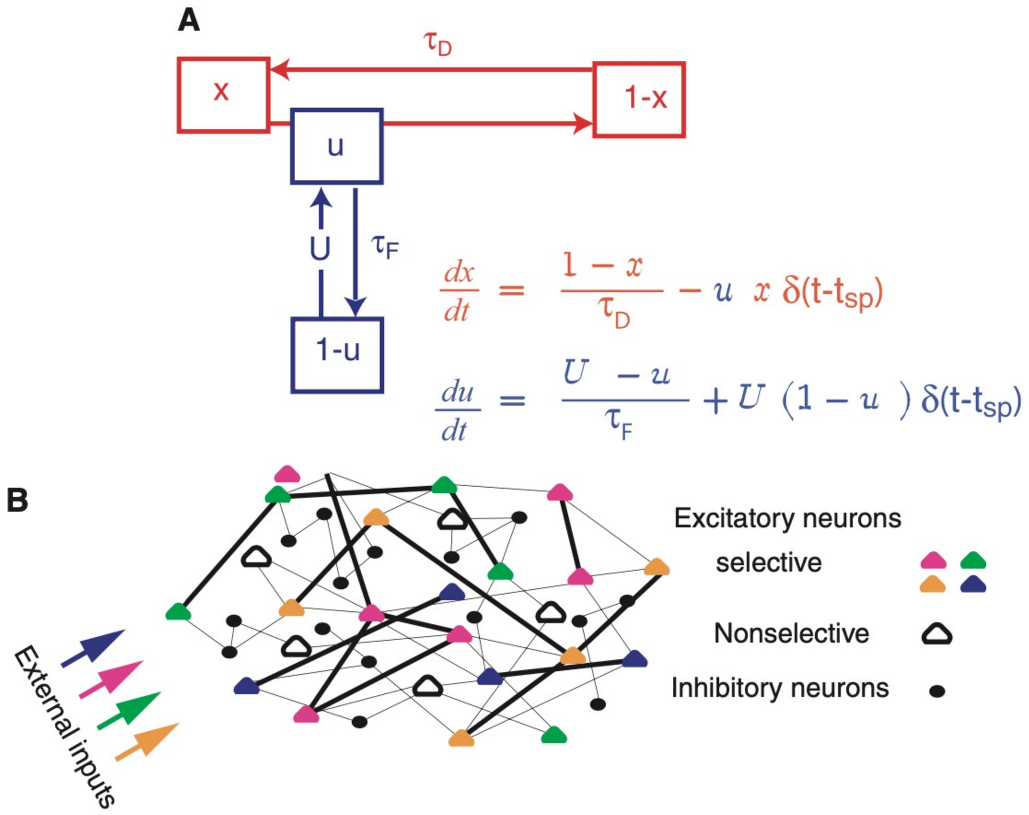


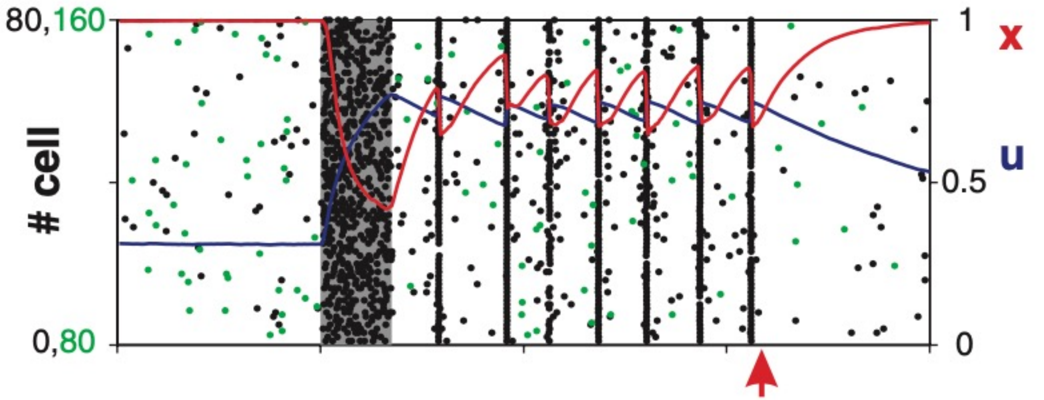
Gamma frequency (~40 Hz) oscillations are nested within slow theta frequency (~7 Hz) oscillations

Lisman and Idiart (1995)

Short-term Information Storage

- Recently, Mongillo et al. proposed a synaptic-based theory for short-term information storage in neural circuits

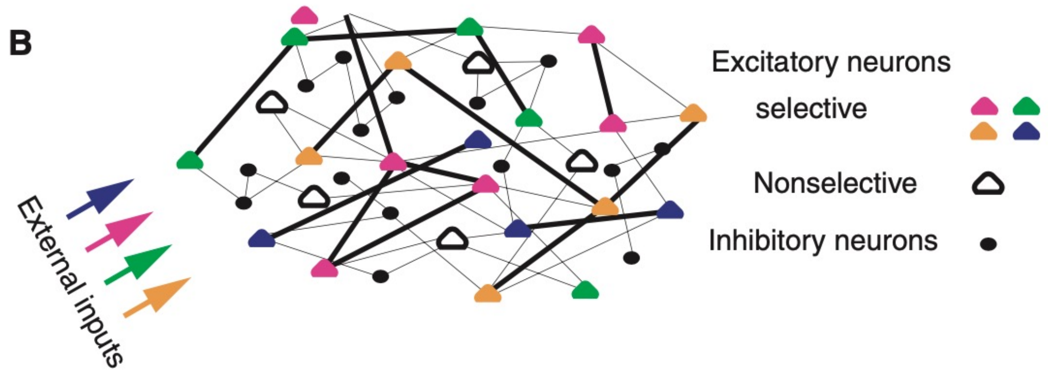




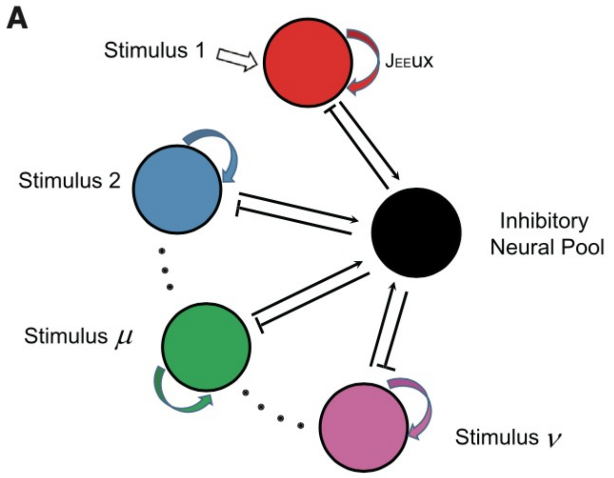
Mongillo et al., 2008

Mean Field Theory

- Approximate the original by averaging over degrees of freedom (the number of values in the final calculation of a statistic that are free to vary).
- Such models consider many individual components that interact with each other.
- In MFT, the effect of all the other individuals on any given individual is approximated by a single averaged effect, thus reducing a many-body problem to a one-body problem.



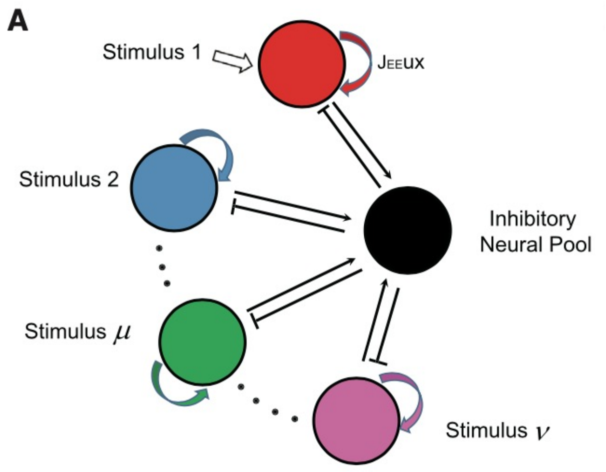
Neurons
Spiking

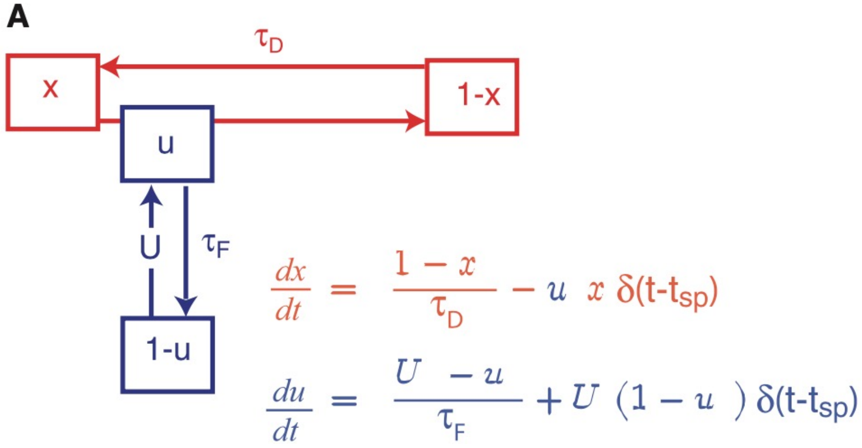


Cluster
Firing rate

STP for Firing Rate Model

- P excitatory clusters
- synaptic current h_μ
- two STP variables u_μ and x_μ
- cluster μ; $\mu = 1, \dots, P$
- inhibitory pool current h_I
- I_b is the constant background excitation → attention
- I_e is the external input





$$\tau \frac{dh_\mu}{dt} = -h_\mu + J_{EE} u_\mu x_\mu R_\mu - J_{EI} R_I + I_b + I_e(t)$$

$$\frac{du_\mu}{dt} = \frac{U - u_\mu}{\tau_f} + U(1 - u_\mu) R_\mu$$

$$\frac{dx_\mu}{dt} = \frac{1 - x_\mu}{\tau_d} - u_\mu x_\mu R_\mu,$$

$$\tau \frac{dh_I}{dt} = -h_I + J_{IE} \sum_\mu R_\mu$$

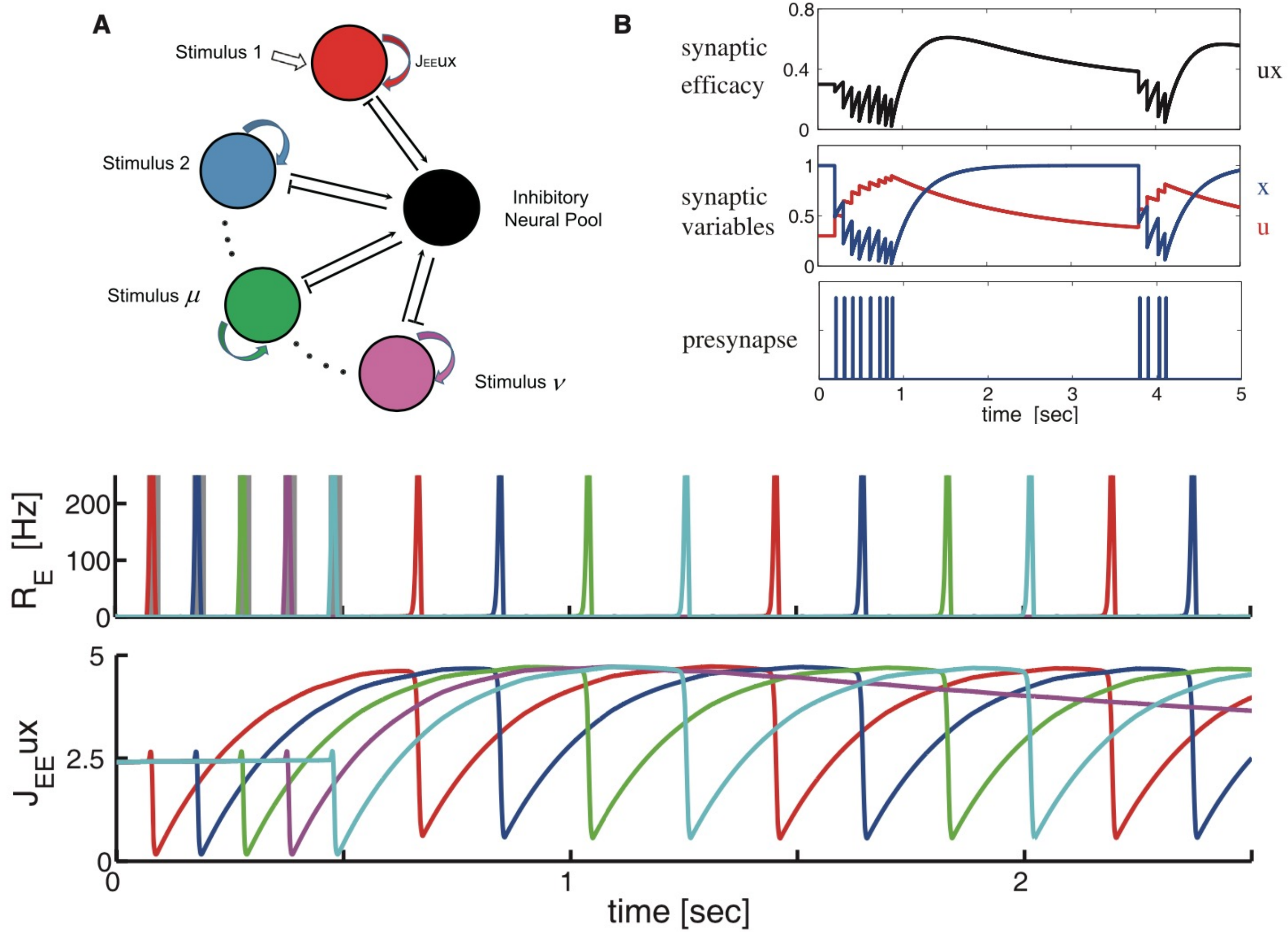
Neurons

Spiking $\delta(t - t_{sp})$

Cluster

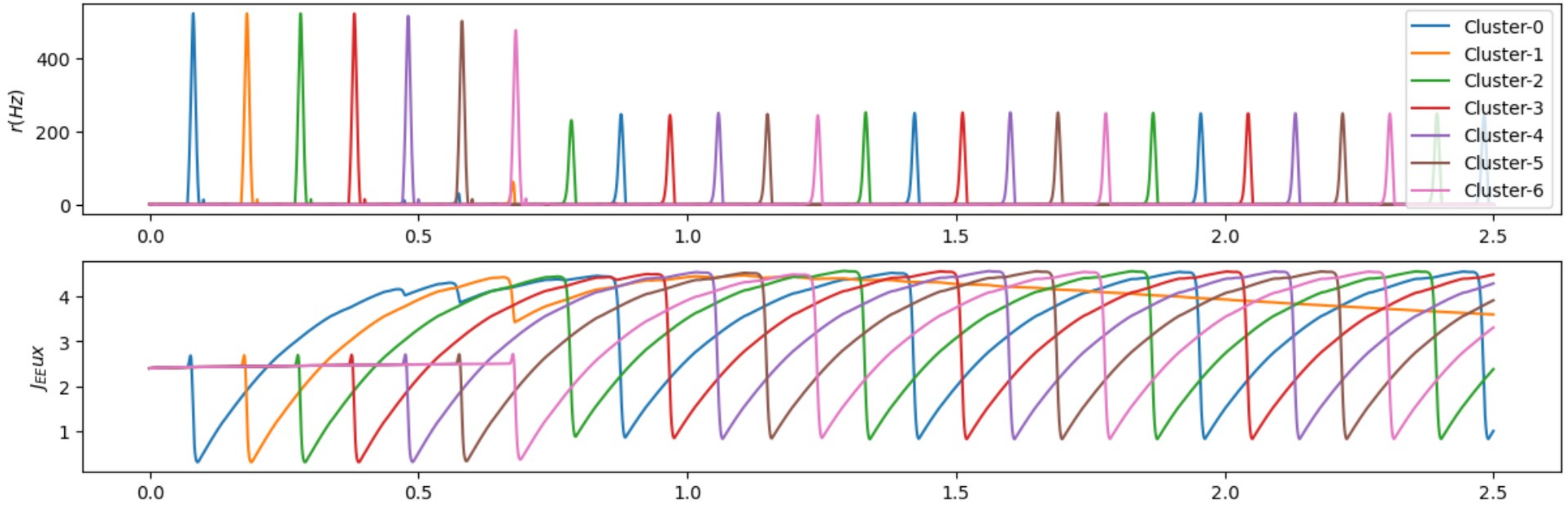
Firing rate R_μ $R(h) = \alpha \ln(1 + \exp(h/\alpha))$

Results

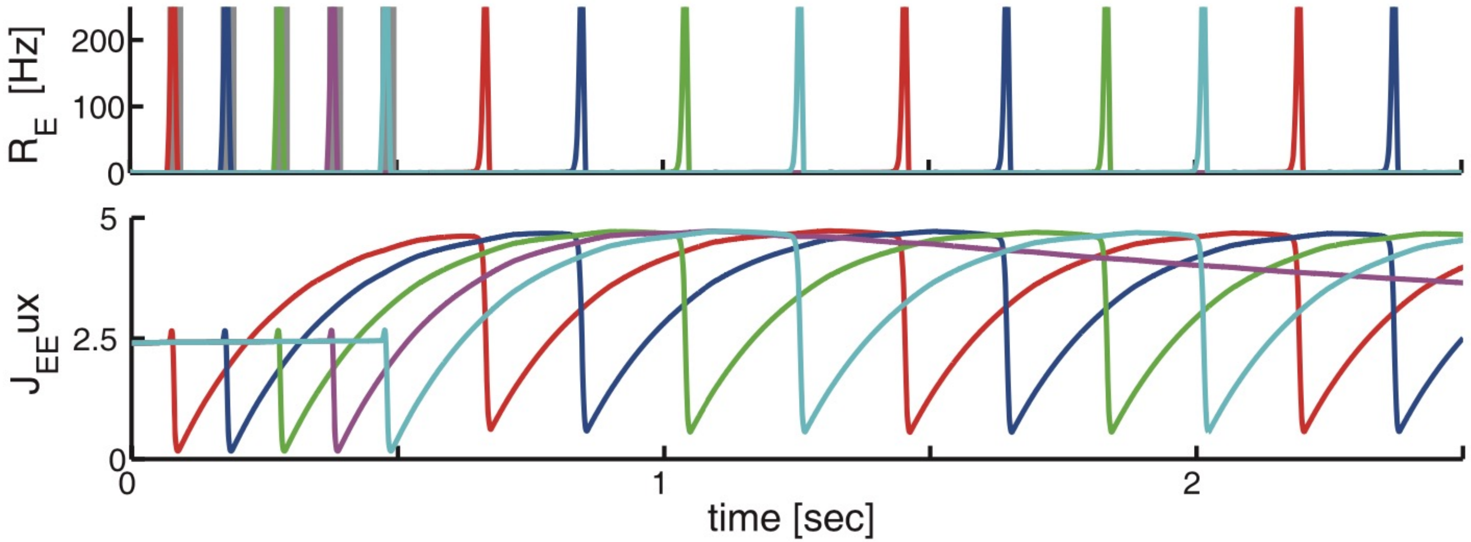


A
Stimulus 1
JEEux
Stimulus 2
Inhibitory
Neural Pool
Stimulus μ
Stimulus ν
B
synaptic
efficacy
ux
synaptic
variables
x
u
presynapse
time [sec]
R_E [Hz]
J_EE ux
time [sec]

Results

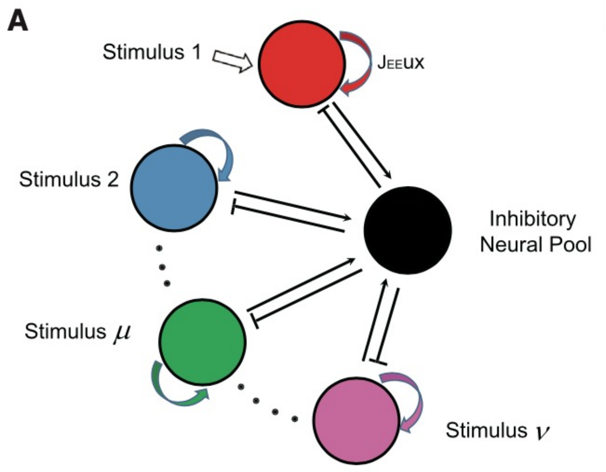


r(Hz)
400
200
0
0.0
0.5
1.0
1.5
2.0
2.5
Cluster-0
Cluster-1
Cluster-2
Cluster-3
Cluster-4
Cluster-5
Cluster-6
$J_{EE}ux$
4
3
2
1
0.0
0.5
1.0
1.5
2.0
2.5



R_E [Hz]
200
100
0
$J_{EE}{}^{ux}$
5
2.5
0
0
1
2
time [sec]

WM in BrainPy




```
# sthe parameters of network
alpha = 1.5
J_EE = 8.  # the connection strength in each excitatory neural clusters
J_IE = 1.75  # Synaptic efficacy E → I
J_EI = 1.1  # Synaptic efficacy I → E
tau_f = 1.5  # time constant of STF  [s]
tau_d = .3  # time constant of STD  [s]
U = 0.3  # minimum STF value
tau = 0.008  # time constant of firing rate of the excitatory neurons [s]
tau_I = tau  # time constant of firing rate of the inhibitory neurons

Ib = 8.  # background input and external input
Iinh = 0.  # the background input of inhibtory neuron

cluster_num = 16  # the number of the clusters
```

```
# the parameters of external input

stimulus_num = 5
Iext_train = 225  # the strength of the external input
Ts_interval = 0.070  # the time interval between the consequent external input [s]
Ts_duration = 0.030  # the time duration of the external input [s]
duration = 2.500  # [s]
```

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```python
@staticmethod
@bp.odeint
def int_exc(u, x, h, t, r, r_inh, Iext):
    du = (U - u) / tau_f + U * (1 - u) * r
    dx = (1 - x) / tau_d - u * x * r
    dh = (-h + J_EE * u * x * r - J_EI * r_inh + Iext + Ib) / tau
    return du, dx, dh

@staticmethod
@bp.odeint
def int_inh(h, t, r_exc):
    return (-h + J_IE * np.sum(r_exc) + Iinh) / tau_I

@staticmethod
def log(h):
    return alpha * np.log(1. + np.exp(h / alpha))

def update(self, _t):
    self.u, self.x, self.h = self.int_exc(self.u, self.x, self.h, _t, self.r, self.inh_r, self.input)
    self.r = self.log(self.h)
    self.inh_h = self.int_inh(self.inh_h, _t, self.r)
    self.inh_r = self.log(self.inh_h)
    self.input[:] = 0.
```

$$\frac{du_\mu}{dt} = \frac{U - u_\mu}{\tau_f} + U(1 - u_\mu)R_\mu$$

$$\frac{dx_\mu}{dt} = \frac{1 - x_\mu}{\tau_d} - u_\mu x_\mu R_\mu,$$

$$\tau\frac{dh_\mu}{dt} = -h_\mu + J_{EE}u_\mu x_\mu R_\mu - J_{EI}R_I + I_b + I_e(t)$$

$$\tau\frac{dh_I}{dt} = -h_I + J_{IE}\sum_\mu R_\mu$$

$$R(h) = \alpha\ln(1 + \exp(h/\alpha))$$