

ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE



Week 3 – part 2: Synaptic Short-Term plasticity



↓ 3.1 Synapses

3.2 Short-term plasticity

3.3 Dendrite as a Cable

3.4 Cable equation

3.5 Compartmental Models - active dendrites?

Welcome to Part 2 of Week 3. So what is short-term synaptic plasticity?

Notes

Summary



0m 04s

Neuronal Dynamics – 3.2 Synaptic Short-Term Plasticity

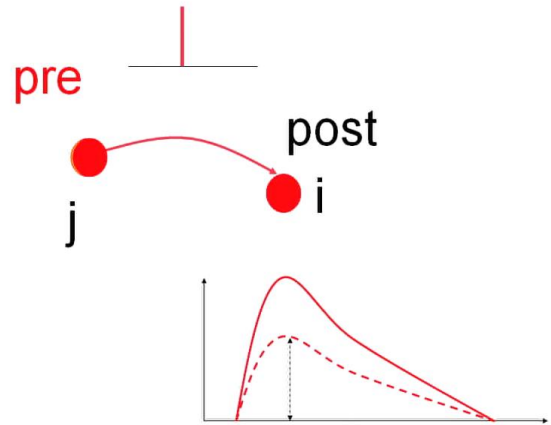
Short-term plasticity/ fast synaptic dynamics

Thomson et al. 1993

Markram et al 1998

Tsodyks and Markram 1997

Abbott et al. 1997



🔗 ✎ 📄 ➡

If a spike is sent off from a neuron and received at the post-synaptic neuron, it causes some effect. Effect be described as a change in the synaptic conductance, which gives rise to a stimulating current. If you simplify that picture and say essentially at the dendrite it's a positive membrane, you can write down the positive membrane equation and find that there's a change in the potential of the post-synaptic cell. An incoming spike causes a post-synaptic potential. You can measure this post-synaptic potential or you can measure the post-synaptic current. And what you find is that increases, goes through a maximum, and then decays back. Now, the strength of the synapse is related to the amplitude of this post-synaptic response. Importantly for the following, this strength is not fixed. Rather, it can change. Synapses can change their strength. Synapses are plastic. And this has been known for quite a long time. How can you see these changes of synaptic strength?

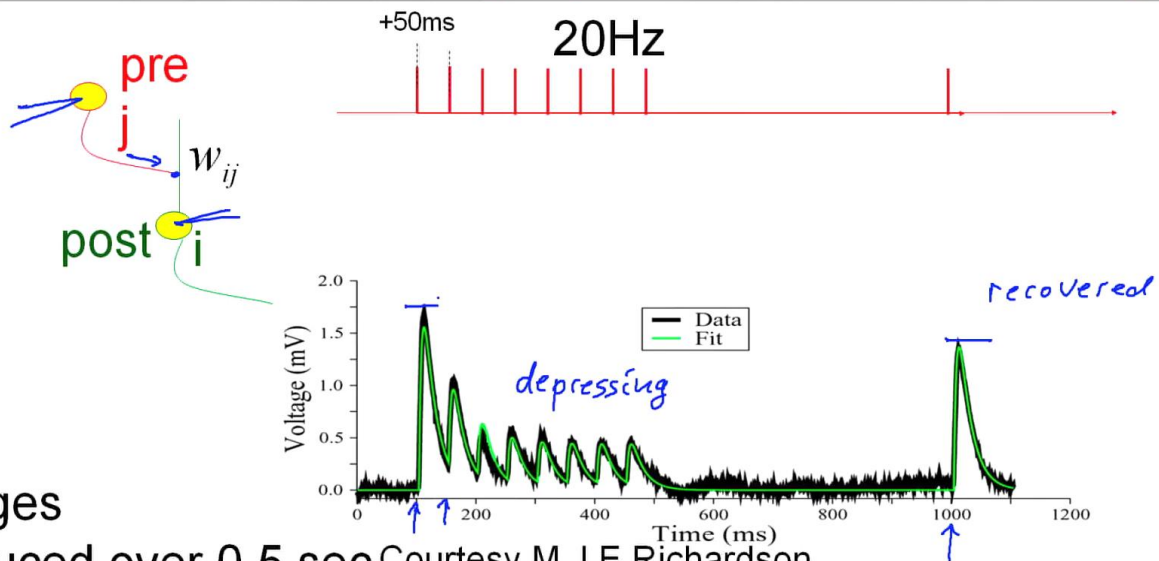
Notes

Summary



0m 13s

Neuronal Dynamics – 3.2 Synaptic Short-Term Plasticity



Changes

- induced over 0.5 sec
 - recover over 1 sec
- Courtesy M.J.E Richardson
Data: G. Silberberg, H. Markram
Fit: M.J.E. Richardson (Tsodyks-Pawelzik-Markram model)

⏏ / ☐ ➡

Well, a famous protocol is to inject a sequence of short pulses into a pre-synaptic neuron so that this pre-synaptic neuron fires, for example, eight action potentials, which travel along the dendrite, arrive at the synapse, and cause a response measured in the post-synaptic cell. Now, the first spike arrives here, and it causes a big response. A second spike arrives, it causes a much smaller response. The third spike, fourth spike, all of the subsequent responses are weaker. The synapse becomes depressed. So this is a synapse with depressive behavior, a depressing synapse. Now, if we wait about 500 milliseconds and give another spike, then you see that the synapse has recovered. It's nearly back to its original value. The strength is nearly back to its original value.

Notes

Summary



1m 34s

Neuronal Dynamics – 3.2 Model of Short-Term Plasticity

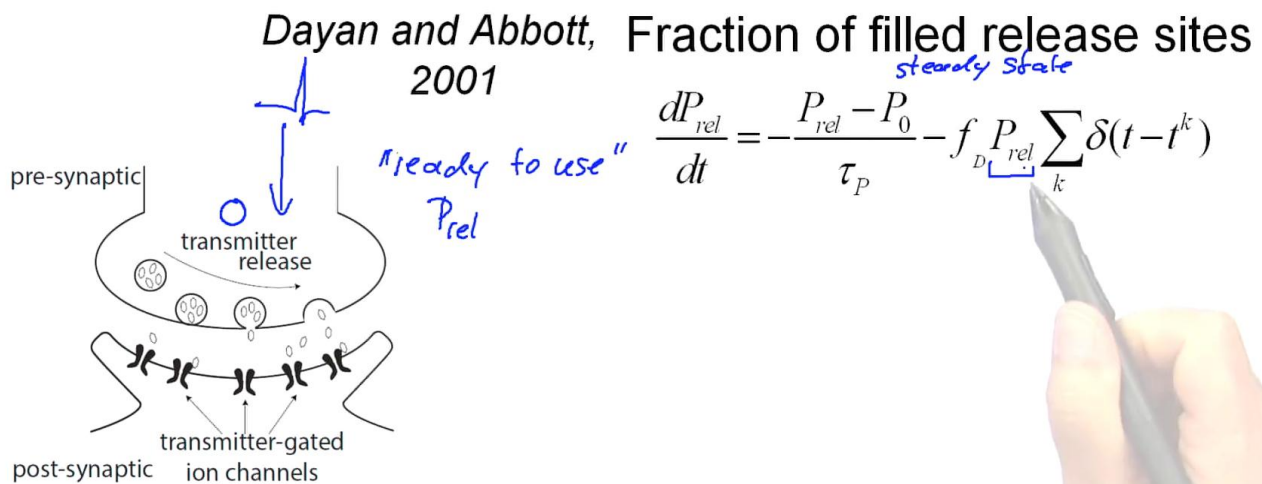


image: Neuronal Dynamics,
Cambridge Univ. Press

So how could we model the observed effects of synaptic depression? As we have seen in Part 1 of this week, inside the pre-synaptic terminals, there are vesicles filled with neurotransmitter. Not all vesicles are in the state ready to use. In the state they are already close to the membrane so that they can open upon the arrival of the signal and spill out the neurotransmitter. So amongst the total number of vesicles that are around, some sit just inside the cell useless and the certain fraction is ready to use. And this fraction will be called P_{rel} . Now in a steady state transmitter molecules are forced back into the vesicles, vesicles will dock on the membrane. So there's a steady state where a certain fraction P_0 of vesicles are ready to use. If there's a deviation from P_0 , it takes a time τ_p to go back to the steady state. That's an exponential approach back to the steady state characterized by this time constant τ_p . But now suppose a spike arrives. A spike arrives, and this spike causes that the vesicles open and send out the molecules into the synaptic cleft. So in fraction of these P_{rel} , this fraction f_D will merge with the membrane and will be empty afterwards.

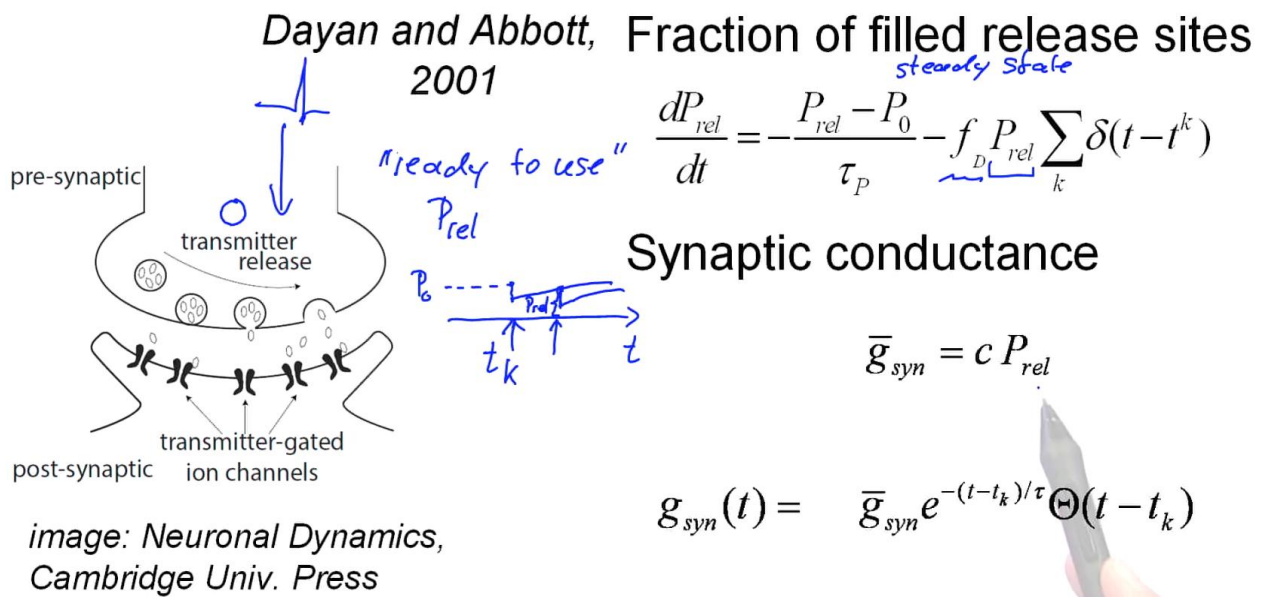
Notes

Summary



2m 50s

Neuronal Dynamics – 3.2 Model of Short-Term Plasticity



Since they empty afterwards, they are no longer ready to use. So normally, as a function of time, we are at the steady state P_0 . Now a spike comes in at time t_k , and because of this spike a certain fraction is used, and then it takes some time to go back to the normal state. P_{rel} is this momentary distance between 0 and this curve. So this is P_{rel} . If there's a next spike coming in here, then a fraction of the now available neurotransmitter vesicles will be used. So with each spike, we'd go down. But we can never go below 0 because of this multiplicative factor P_{rel} . Now, what's the use of P_{rel} ? Well, the total synaptic conductance will be determined by the amount of neurotransmitter that can be captured. But if less neurotransmitter is spilled out, less neurotransmitter is around. So the total synaptic conductance is limited by this factor P_{rel} . And in a simple model of the synaptic conductance, we would just have an exponential pulse that's controlled by the amount of neurotransmitter that's around.

Notes

Summary



Neuronal Dynamics – 3.2 Model of synaptic facilitation

4 + 1 pulses $\tau_P = 200ms$

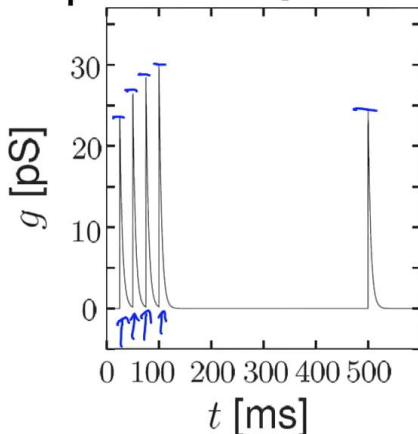


image: Neuronal Dynamics,
Cambridge Univ. Press

Fraction of filled release sites

$$\frac{dP_{rel}}{dt} = -\frac{P_{rel} - P_0}{\tau_P} + f_F \underbrace{(1 - P_{rel})}_{\text{saturation}} \sum_k \delta(t - t_k)$$

Synaptic conductance

$$\bar{g}_{syn} = c P_{rel}$$

$$g_{syn}(t) = \bar{g}_{syn} e^{-(t-t_k)/\tau} \Theta(t-t_k)$$

Dayan and Abbott, 2001

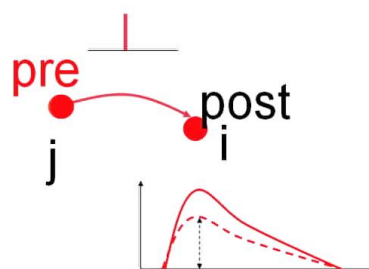
So let's see how this model works. Here we have a sequence of four pulses. First pulse causes a synaptic response. Second pulse causes a reduced response. Third pulse, the response is reduced further. Fourth pulse, the response is nearly 0. And then it takes some time to recover the response back to the normal value, and this recovery time was set here to 400 milliseconds. Many synapses show depression, but some synapses also show facilitation. Facilitation is the inverse effect. With each spike, the response gets stronger. The first pulse that arrives causes the response of this size. The second pulse a stronger response. The third pulse an even stronger response, and so forth. And then it takes some time to recover back to the normal value in this model simulation if it was set to 200 milliseconds. The model is, in fact, analogous to the previous one. There's always a certain amount of vesicles in the state ready to use, ready to be released, and there could be more ready to be released. And with each spike, out of those that are not yet in the state ready to be released, a certain fraction is recruited. Is moved, say, close to the membrane so that it can be released at the next spike arrival. So this factor $1 - P_{rel}$ causes a saturation and it assures that P_{rel} can never grow beyond its maximum value of 1.

Notes

Summary



Neuronal Dynamics – 3.2 Summary



Synapses are not constant

- Depression
- Facilitation

Models are available

- Tsodyks-Pawelzik-Markram 1997
- Dayan-Abbott 2001

To summarize, synapses are not constant. They change all the time. Synapses show facilitation. They can get stronger. They show depression. They can get weaker. The model I've discussed here can be found in the book of Dayan and Abbott. It's a simple model which treats facilitation and depression separately. There is a slightly more complicated model, but of the same structure, of the same type by Markram-Tsodyks-Pawelzik which allows to describe facilitation and this depression within the same synapse, because that's observed. Some synapses show both, facilitation and depression. So with this, I would like to close our discussion of synapses.

Notes

Summary



8m 40s

Neuronal Dynamics – Quiz 3.2

Multiple answers possible!

Time scales of Synaptic dynamics

- ☐ The rise time of a synapse can be in the range of a few ms.
- ☐ The decay time of a synapse can be in the range of few ms.
- ☐ The decay time of a synapse can be in the range of few hundred ms.
- ☐ The depression time of a synapse can be in the range of a few hundred ms.
- ☐ The facilitation time of a synapse can be in the range of a few hundred ms.

Synaptic dynamics and membrane dynamics.

Consider the equation

$$(*) \quad \frac{dx}{dt} = -\frac{x}{\tau} + c \sum_k \delta(t - t^k)$$

With a suitable interpretation of the variable x and the constant c

- ☐ Eq. (*) describes a passive membrane voltage $u(t)$ driven by spike arrivals.
- ☐ Eq. (*) describes the conductance $g(t)$ of a simple synapse model.
- ☐ Eq. (*) describes the maximum conductance $\bar{g}_{syn}$ of a facilitating synapse

Please take some time to look at the quiz that we have prepared for you.

Notes

Summary



9m 38s

Neuronal Dynamics – 3.2 Literature/short-term plasticity

Dayan, P. and Abbott, L. F. (2001). Theoretical Neuroscience. MIT Press, Cambridge.

Abbott, L. F., Varela, J. A., Sen, K., and Nelson, S. B. (1997). Synaptic depression and cortical gain control. *Science* 275, 220–224.

Markram, H., and Tsodyks, M. (1996a). Redistribution of synaptic efficacy between neocortical pyramidal neurons. *Nature* 382, 807–810.

A.M. Thomson, Facilitation, augmentation and potentiation at central synapses, *Trends in Neurosciences*, 23: 305–312 ,2001

Tsodyks, M., Pawelzik, K., and Markram, H. (1998). Neural networks with dynamic synapses. *Neural. Comput.* 10, 821–835.



And here's also some literature for synaptic facilitation, depression, and synaptic modeling.

Notes

Summary



9m 43s