

ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

EPFL, Lausanne, Switzerland



EPFL



Week 7 – part 2a : AdEx: Adaptive exponential integrate-and-fire



✓ 7.1 What is a good neuron model?

- Models and data

7.2 AdEx model

- Firing patterns and adaptation

7.3 Spike Response Model (SRM)

- Integral formulation

7.4 Generalized Linear Model

- Adding noise to the SRM

7.5 Parameter Estimation

- Quadratic and convex optimization

7.6. Modeling in vitro data

- how long lasts the effect of a spike?

7.7. Helping Humans

Welcome to lecture two with the final week of the class neural dynamics. I finished the previous lecture with the statement that things are missing in the non-linear integrate and fire model, and it can account for adaptation, and it can't account for different firing patterns. Now let's address these issues now.

Notes

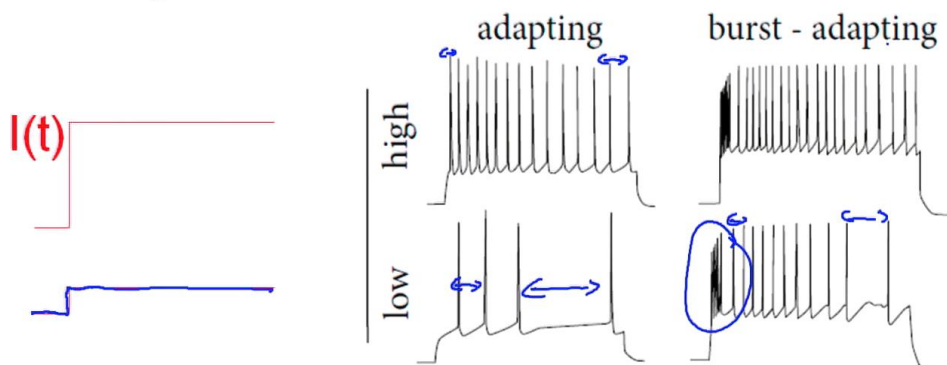
Summary



0m 04s

Neuronal Dynamics – 7.2 Adaptation

Step current input – neurons show adaptation



Data:
Markram et al.
(2004)

What is adaptation? Well, an experimentalist injects routinely a step current into neurons, and he observes the behavior. And, typically, what you find quite often is a behavior like this. There are first a sequence of spikes with very short interspike intervals. And as we wait, the interspike intervals get longer and longer. This is called adaptation. For small input, the effect is sometimes very big. The final interspike interval is much longer than the first one. If you increase the input current, the neuron is still adapting. Overall, the interspike intervals are shorter compared to the low input case, but still, it's true that the final interspike interval is longer than the first one. That's adaptation. Now, some neurons show sort of an extreme form of adaptation. In fact, it's not just adaptation. There's a burst at the beginning, at the [INAUDIBLE] caused by the step input current. And afterwards, the neuron is still adapting. The initial intervals are shorter than the final one. So this kind of behavior has been described as initial burst followed by adaptation. And there are many, many other firing patterns.

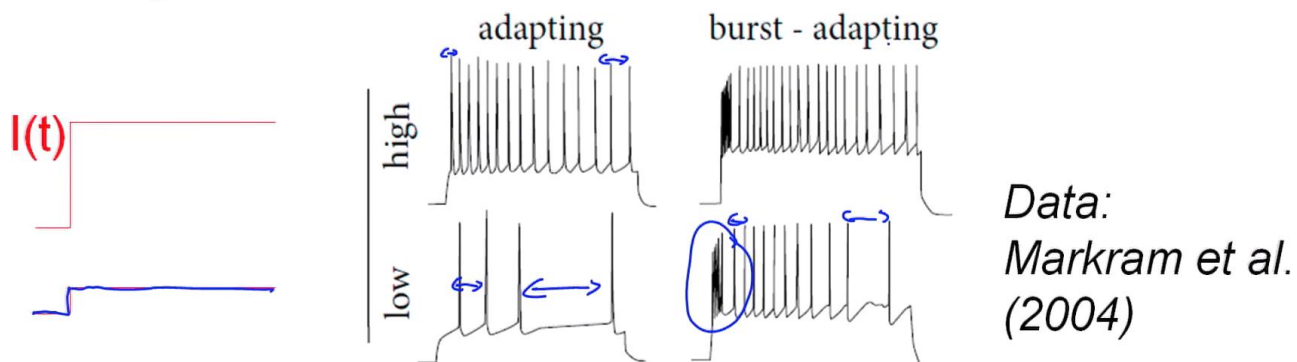
Notes

Summary



Neuronal Dynamics – 7.2 Adaptation

Step current input – neurons show adaptation



1-dimensional (nonlinear) integrate-and-fire model cannot do this!

Now, one-dimensional non-linear integrate and fire models cannot account for this kind of adaptation or burst-adapting neurons.

Notes

Summary



2m 12s

Neuronal Dynamics – 7.2 Adaptive Exponential I&F

Add adaptation variables:

$$\tau \frac{du}{dt} = -(u - u_{rest}) + \Delta \exp\left(\frac{u - \vartheta}{\Delta}\right) - R \sum_k w_k + RI(t)$$

$$\tau_k \frac{dw_k}{dt} = a_k (u - u_{rest}) - w_k + b_k \tau_k \sum_{f.} \delta(t - t^f)$$

firing times

after each spike w_k
jumps by an amount b_k

What can you do about this? Well, the answer is let's add adaptation variables. Remember, the exponential integrate and fire model has a linear term, it has an exponential term, and then it has a current. This is the driving current, normally. Now, here, the driving current is really given by other variables, w . These are auxiliary variables called adaptation variables. And, of course, there's still the external input current. Units of this equation are such that we have voltage here on the right-hand side. So R times i is voltage. R times w is voltage. So w has the same units as i . It has units of a current. Now, for each of these adaptation variables, you can write down a linear differential equation. So dw/dt has decay term minus w . It would normally go back to w equals 0. However, if the voltage is above its resting value, then this drives w to a somewhat higher value, to a nonzero value. The coupling between the voltage and the w variables is a . And then there's an extra coupling, a coupling course by spikes. These are the firing times of the neuron. f runs from 1 to 3 to 4 to 5, so this is a spike counter, and this is the other function.

Notes

Summary



Neuronal Dynamics – 7.2 Adaptive Exponential I&F

Add adaptation variables:

$$\tau \frac{du}{dt} = -(u - u_{rest}) + \Delta \exp\left(\frac{u - \vartheta}{\Delta}\right) - R \sum_{k=1}^5 w_k + RI(t)$$

$$\tau_k \frac{dw_k}{dt} = a_k (u - u_{rest}) - w_k + b_k \tau_k \sum_f \delta(t - t^f)$$

firing times

Exponential I&F
+ 1 adaptation var.
= AdEx

SPIKE AND RESET

after each spike w_k
jumps by an amount b_k

AdEx model,
Brette & Gerstner (2005):

If $u = \theta_{reset}$ then reset to $u = u_r$

Now, essentially, this means that after each spike, the value of the w variable is increased by this amount, b_k . You can have several of these other adaptation variables, running from one to five, for example. And that's why we have this index k here. τ_k is a time constant of this w variable, number k . a_k is the coupling parameter for this w variable. Often, we only work with one single adaptation variable. Now, in the general case, you have already set that. After each spike, the w variable jumps by an amount, b_k . As in the simple integrate and fire model, at each spike-- and a spike is detected if the voltage reaches the reset threshold-- after each spike, we reset two new initial values, u_r . Note that this is reset to while this is jumps by. It makes a difference, as we will see in the following. So this is the general situation. We could have, for example, five of these adaptation variables. The simplest case is that we only have one adaptation variable. In this case, we don't need the index k . In this case, it's called the adaptive exponential integrate and fire model, or short, AdEx.

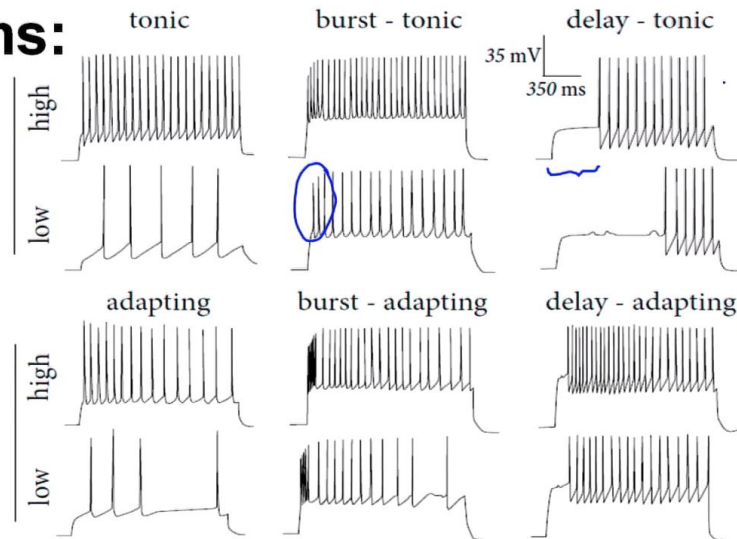
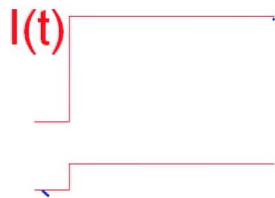
Notes

Summary



Firing patterns:

Response to
Step currents,
Exper. Data,
Markram et al.
(2004)



Now, what is our aim? We introduced this adaptation variable, one adaptation variable, or possibly many adaptation variables, to account for adaptation, to account for different firing patterns. And I've shown already too much of these firing patterns, and here are more of these. As before, it's a neuron, and an experimentalist injects a step current, a real neuron, in vitro in a cortical slice. Now, this is the case for weak step current that the neuron fires regularly. It fires tonically. If you go to a larger step input, it still fires tonically. Then we have the case that's neuron. Now we go to a different neuron. Then we might find a different result. We may find that, initially, the neuron emits a burst, and then there's a rapid transition to regular periodic firing for low input and also for high input. And then there's-- in yet another neuron, you may find that, if you give the input, there is, indeed, this regular firing. However, it takes a long time, a waiting time or delay, until this tonic firing sets in. Now, other neurons make show other behavior. I've talked about adaptation before, short intervals at the beginning, long intervals later on, possibly combined with an initial burst or with an initial delay.

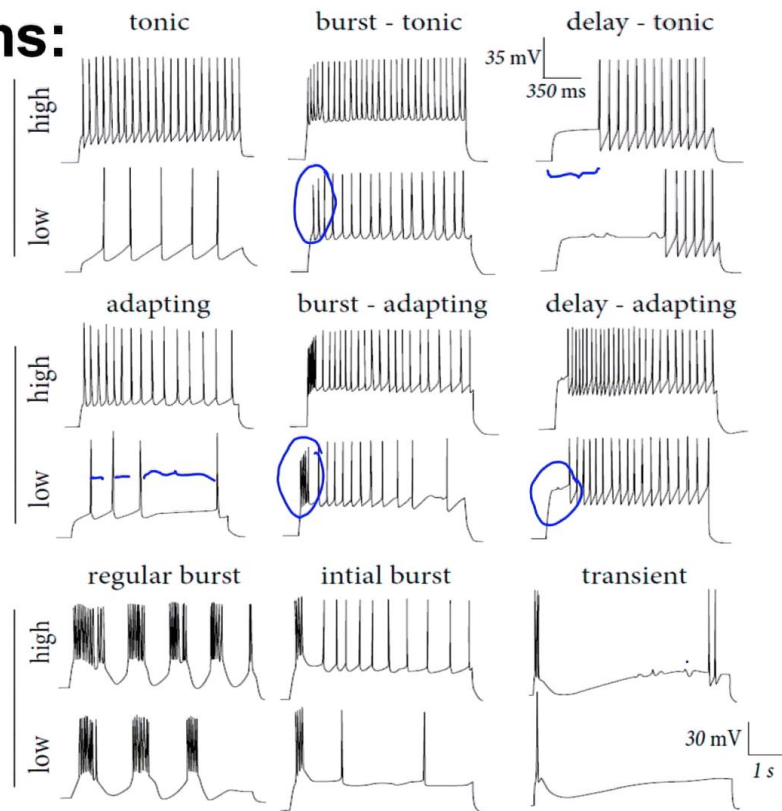
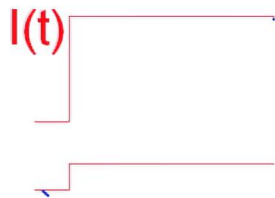
Notes

Summary



Firing patterns:

Response to
Step currents,
Exper. Data,
Markram et al.
(2004)



Again, this line is for the weak input. The upper part is for large steps. Other neurons may show yet a different behavior. Even though the current is held constant after the switch, the neuron exhibits bursting. There's a short sequence, trrt, followed by a pause and then another trrt of many spikes. Trrt, pause. Trrt, pause. Trrt, pause, and so forth. Now, you may find yet other behavior, for example, a short, initial burst followed by a long, delayed transient. In short, there are many different firing behaviors. Now, on the previous slide, I proposed one neuron model, the exponential integrate and fire model with adaptation AdEx.

Notes

Summary



8m 00s

Firing patterns:

Response to
Step currents,
AdEx Model,
Naud&Gerstner

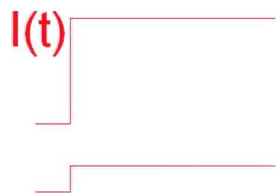
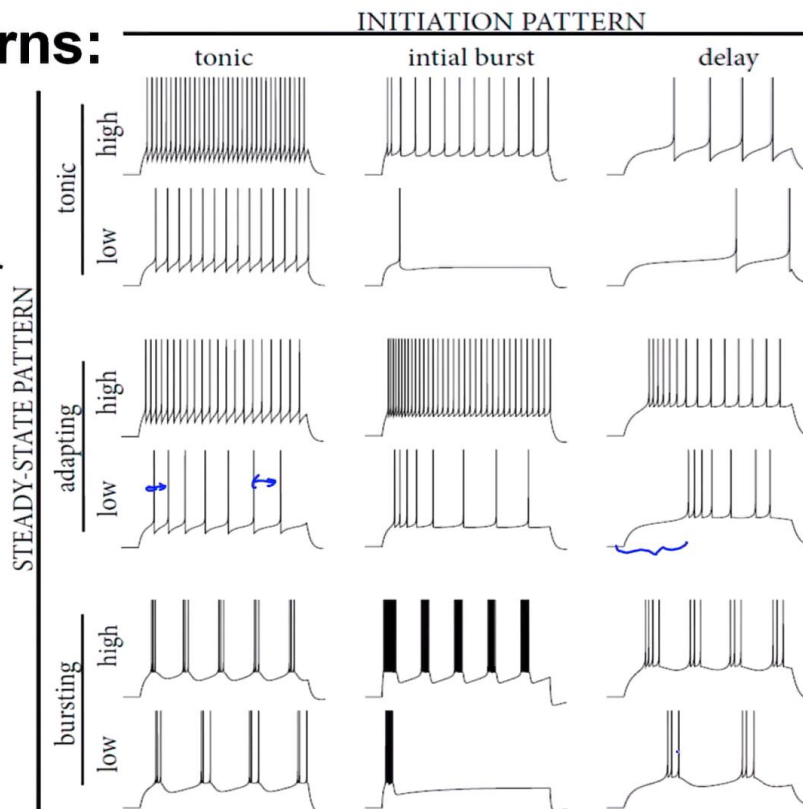


Image:
Neuronal Dynamics,
Gerstner et al.
Cambridge (2002)



Can we account for all these different firing behaviors with just one neuron model? And, surprisingly, the answer is yes. Yes, we can. Here again, the tonic behavior, initial burst, delayed spikes. Here, the case of adaptation, interspike intervals start small and get longer thereafter. There's delayed spike followed by adapting behavior, and there's also bursting, regular bursting, just initial bursting, bursts that start after delay. So there is a variety of different firing patterns in this neuron model, in one single neuron model.

Notes

Summary



9m 07s

Neuronal Dynamics – 7.2 Adaptive Exponential I&F

$$\tau \frac{du}{dt} = -(u - u_{rest}) + \Delta \exp\left(\frac{u - \vartheta}{\Delta}\right) - R w + R I(t)$$
$$\tau_w \frac{dw}{dt} = a (u - u_{rest}) - w + b \tau \sum_f \delta(t - t^f)$$

AdEx model

Phase plane analysis!

Can we understand the different firing patterns?

✎ ✎ ✎ ✎

So the question arises, can we understand these different firing patterns? How can all these different firing patterns arise from a model that looks fairly simple? Well, yes, we can understand it by using phase plane analysis.

Notes

Summary



9m 56s

Neuronal Dynamics – 7.2. Adaptive Exponential I&F



$$\tau \frac{du}{dt} = f(u) - Rw + RI(t)$$

$$\tau_w \frac{dw}{dt} = a(u - u_{rest}) - w$$

-linear + exponential
-adaptation variable

→ Various firing patterns

So I tried to convince you that real neurons show a variety of different firing patterns, and there are simple models with just two equations that can account for this variety of firing patterns. Now, one question is whether we can sit in front of the computer and try to optimize parameters by hand or whether we can predict the type of behavior we are expected to get just looking at our choice of parameters. Phase plane analysis will help for this, and that will be part B of lecture two of this week.

Notes

Summary



10m 18s

Neuronal Dynamics – Quiz 7.2. Nullclines of AdEx

$$\tau \frac{du}{dt} = -(u - u_{rest}) + \Delta \exp\left(\frac{u - \vartheta}{\Delta}\right) - R w + R I(t)$$

$$\tau_w \frac{dw}{dt} = a (u - u_{rest}) - w$$

A - What is the qualitative shape of the w-nullcline?

- ☐ constant
- ☐ linear, slope a
- ☐ linear, slope 1
- ☐ linear + quadratic
- ☐ linear + exponential

B - What is the qualitative shape of the u-nullcline?

- ☐ linear, slope 1
- ☐ linear, slope 1/R
- ☐ linear + quadratic
- ☐ linear w. slope 1/R+ exponential

Notes

Summary

11m 06s

