Spike transmission between electrically coupled sensory neurons is improved by filter properties

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Motivation: Neuromorphic circuits

"The human brain is the most energy-efficient processor around, so it is natural for hardware developers to try to mimic it.

An approach called neuromorphic computing aims to do just that, with technologies that seek to simulate communication and processing in a biological nervous system."

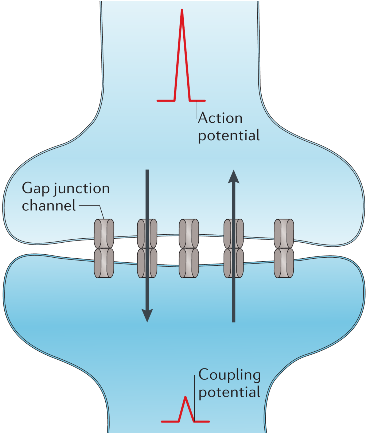
Big data needs a hardware revolution.

Nature editorial, 6th Feb 2018

Electrical synaptic transmission in biological neural networks

Main properties

- Bidirectional
- Without delay
- Reliable: No transmission failures
- Analogic



Modified from Pereda, 2014

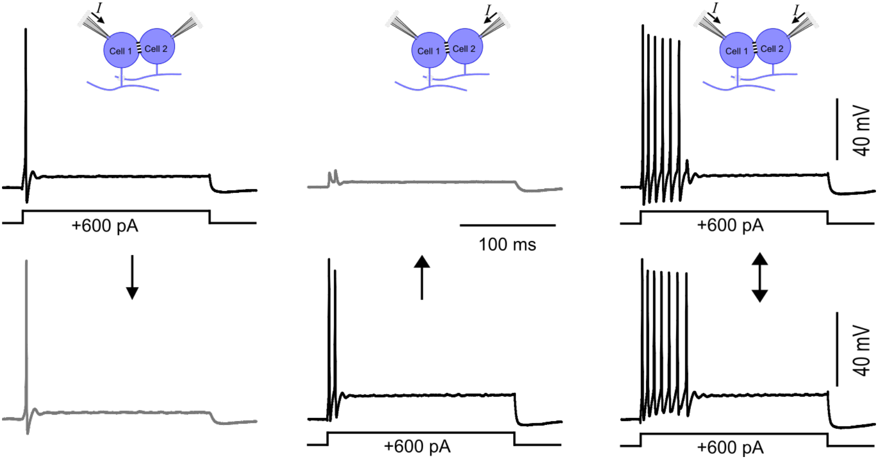
Some emerging properties of electrical synapses in the nervous system

- Synchronization
- Lateral inhibition and excitation
- Coincidence detection
- Signal-to-noise ratio improvement

Coincidence detection

Sensory neurons from the mesencephalic trigeminal nucleus

Coincident inputs increase the effective input resistance in coupled neurons

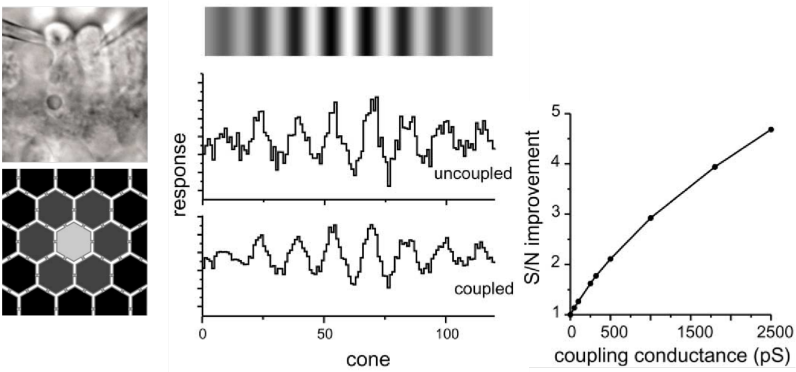


Davoine & Curti, 2019

Example: Signal-to-noise ratio improvement in the retina

Cone photoreceptors

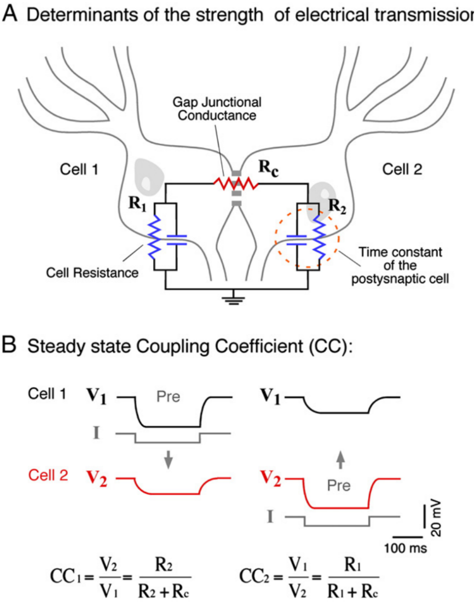
The cones of the retina have intrinsic noise, due to the phototransduction process. Electrical synapses between them attenuate the noise, without affecting the partially shared common visual input.



Modified from De Vries et al., 2002

Strength of electrical synaptic transmission

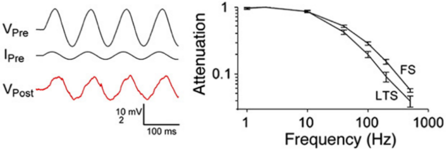
DC signals



Strength of electrical synaptic transmission

Frequency dependence for cortical neurons

Electrical synapses between Fast Spiking (FS) and Low-Threshold Spiking (LTS) cortical neurons act as lowpass filters

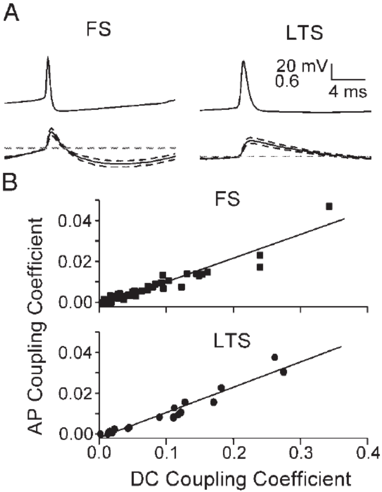


Modified from Pereda et al., 2013

Efficacy of electrical synaptic transmission

Spikes vs DC

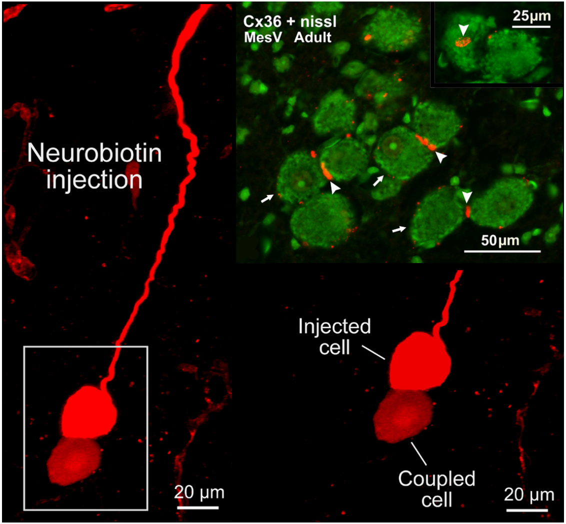
Electrical synapses transmit DC signals more efficiently than spikes in FS and LTS neurons.



Modified from Gibson et al., 2005

Sensory neurons from the mesencephalic trigeminal nucleus

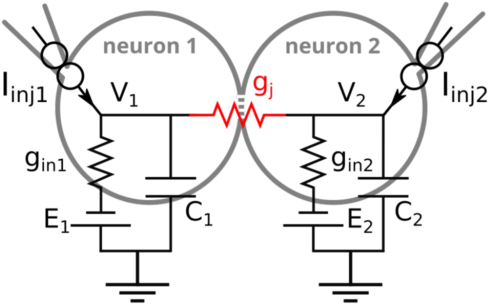
Neurons coupled in pairs, through their somas.

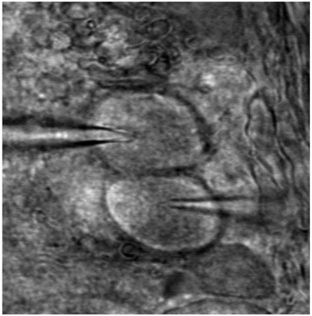


Curti et al., 2012

Patch-clamp whole cell electrophysiological recordings

It is possible to record and stimulate electrically coupled cells, recording their membrane potentials and injecting currents.

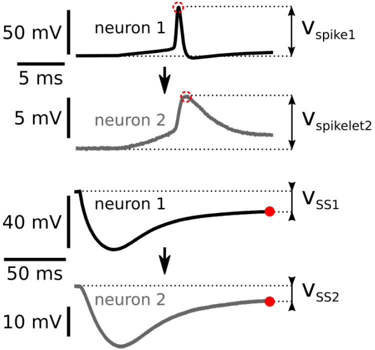


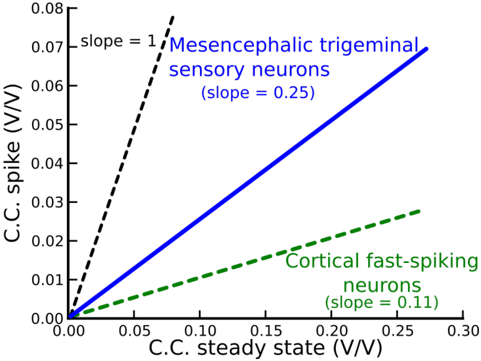


Efficacy of electrical synaptic transmission

Comparative between the attenuation of action potentials and DC signals

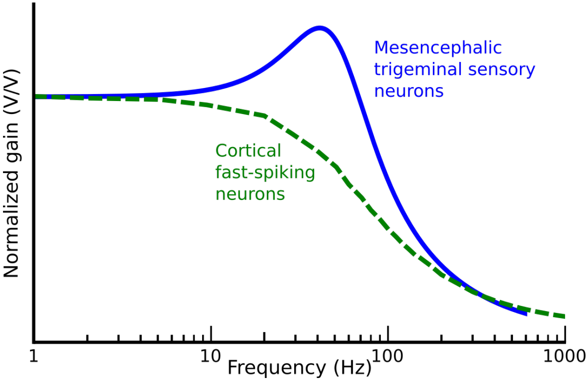
Sensory neurons from the mesencephalic trigeminal nucleus are more efficient at spike transmission than FS neurons.





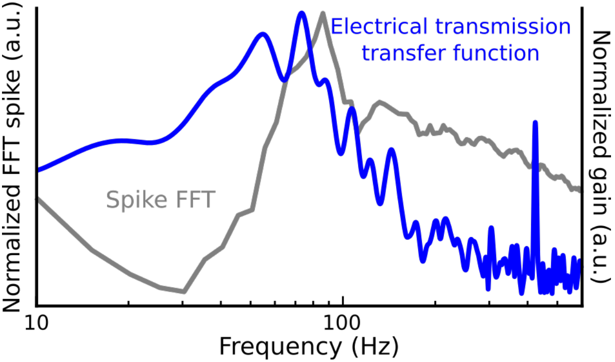
Filter properties of electrical synaptic transmission

The enhanced efficacy of spike transmission is due to the bandpass properties of electrical synaptic transmission in sensory neurons.



Frequency content of spikes

The bandpass filter is better suited to the frequency contents of the spikes.



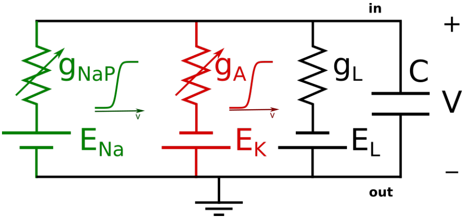
How these sensory neurons improve their efficacy in spike transmission?

Reduced electrical model of a sensory neuron

First, we built a simplified model of one sensory neuron:

Operating close to the Resting Membrane Potential (RMP $= -55$ mV; set point of the neuron) the main ion currents are the leak I_L and:

- Persistent sodium I_{NaP}
- A-type potassium I_A

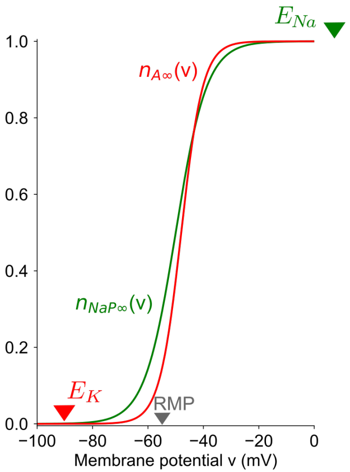


I_{NaP} and I_A have opposite directions, due to the value of their reversal potentials E_{Na} and E_K

Reduced electrical model of a single sensory neuron

$$\begin{cases} \dfrac{dv}{dt} &= \dfrac{1}{C}\left(-I_L - I_{NaP} - I_A\right) \\ I_L &= g_L\left(v - E_L\right) \\ I_{NaP} &= \overline{g}_{NaP} \cdot n_{NaP\infty}\left(v - E_{Na}\right) \\ I_A &= \overline{g}_A \cdot n_A\left(v - E_K\right) \\ \dfrac{dn_A}{dt} &= \dfrac{n_{A\infty} - n_A}{\tau_A} \end{cases}$$

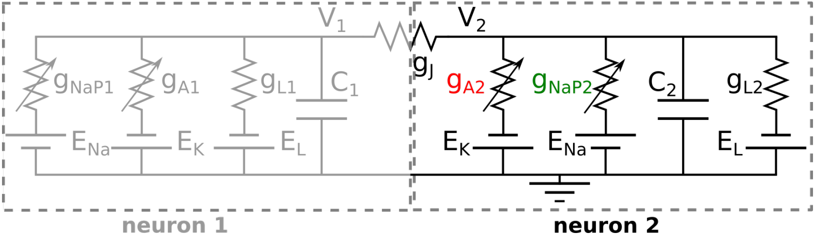
where the asymptotic activation curves $n_{NaP\infty}$ and $n_{A\infty}$ are sigmoid functions of v and $\tau_A = 3.4$ ms.



Reduced model of electrical transmission

Equivalent circuit

To study synaptic transmission close to the resting membrane potential, two simplified neuron models were coupled through a linear conductance g_J, which represents the electrical synapse.



Bandpass behavior in control conditions:

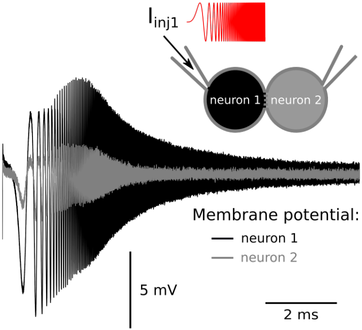
$$H(j\omega) = \frac{g_J\,(1 + j\omega\tau_A)}{(j\omega)^2\,\tau_A C_2 + (C_2 + \Gamma_\infty \tau_A)\,j\omega + \Gamma_0}$$

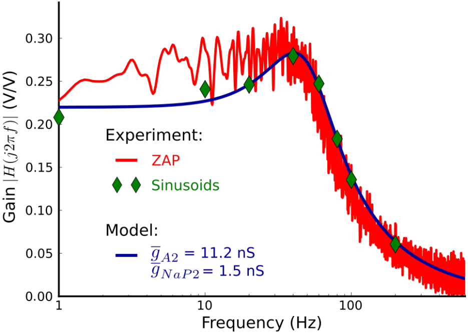
where Γ_∞ and Γ_0 depend on the ion conductances, the activation curves $n_{NaP\infty}$ and $n_{A\infty}$ and their voltage derivatives.

The reduced model explains the filter properties of electrical transmission

Control conditions

The membrane potentials of both neurons were recorded while injecting ZAP (chirp) or sinusoidal currents to one of them. The transfer function was obtained as the ratio of their FFT.





The reduced model explains the filter properties of electrical transmission

I_{NaP} and I_A blocked

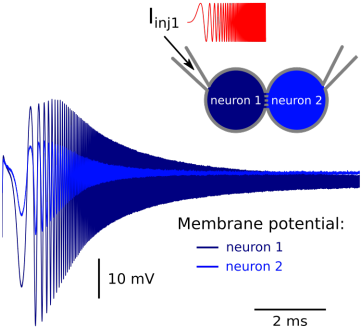
If I_{NaP} and I_A are blocked, the filter becomes lowpass:

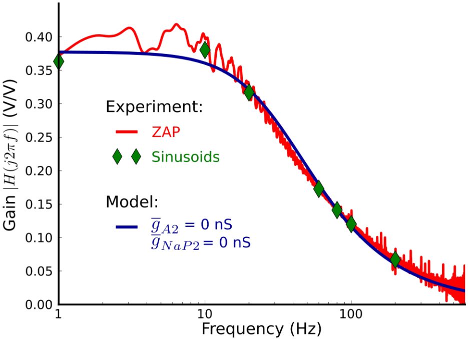
$$H_{\text{passive}}(j\omega) = \frac{g_J}{g_J + g_{L2} + j\omega C_2}$$

The reduced model explains the filter properties of electrical transmission

I_{NaP} and I_A blocked

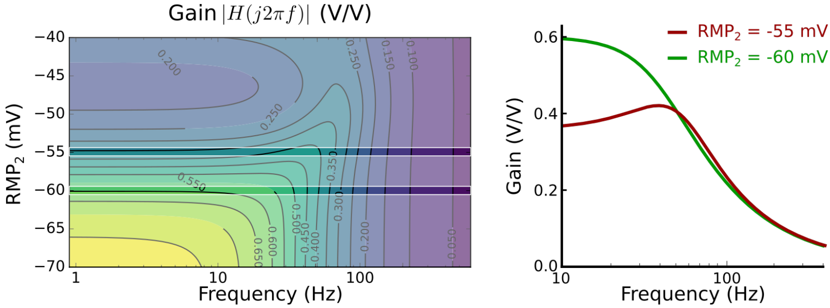
When I_{NaP} and I_A are pharmacologically blocked, the electrical synapse becomes a lowpass filter.





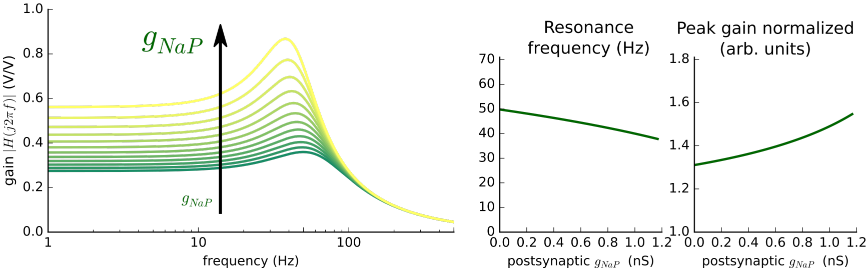
Bandpass behavior is displayed at the resting membrane potential of the neuron

The filter properties depend on the set point of the neuron. If it changes (as may happen in pathological conditions), the bandpass turns into a lowpass.



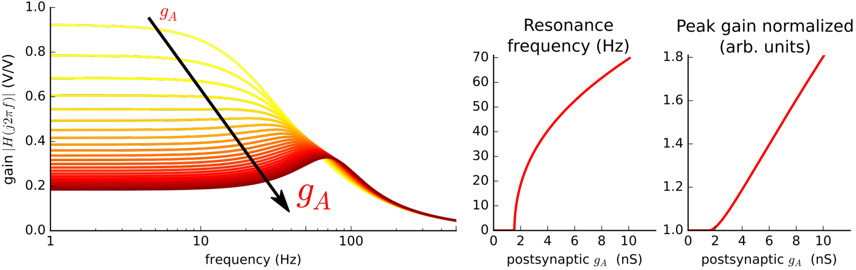
The persistent sodium current I_{NaP} amplifies the gain

I_{NaP} acts as an amplifying mechanism, without modifying the shape of the filter.



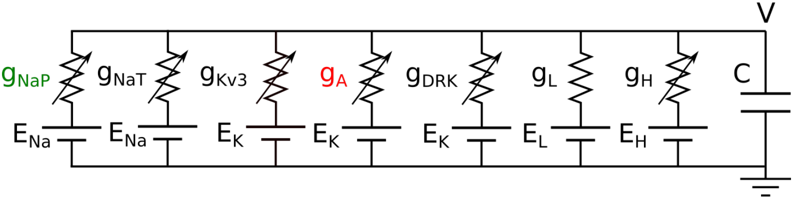
The A-type potassium current I_A is responsible for the bandpass behavior

I_A introduces the resonance. DC signals become more attenuated than faster ones, like the spikes.



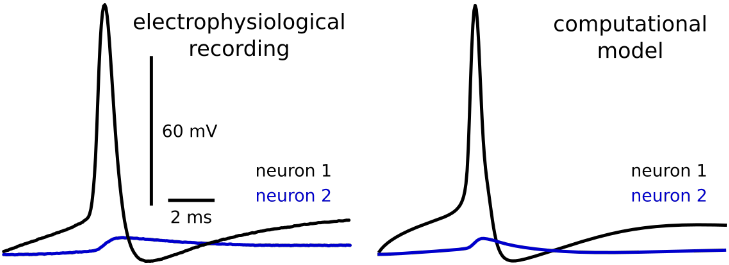
Realistic neuron model from electrophysiological recordings

We added more ion currents to the reduced model, in order to have a realistic model with spikes.



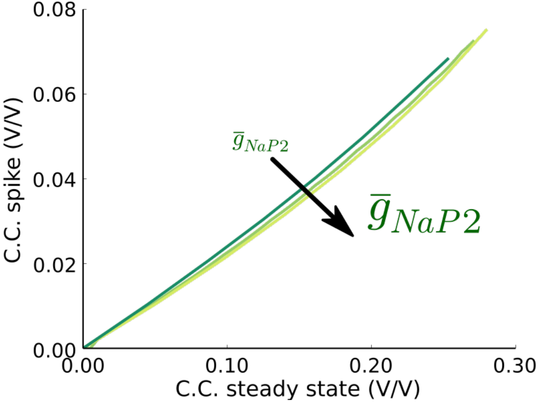
Realistic neuron model from electrophysiological recordings

The parameters of the realistic model were obtained by fitting electrophysiological recordings, using an evolutionary multi-objective optimization algorithm.



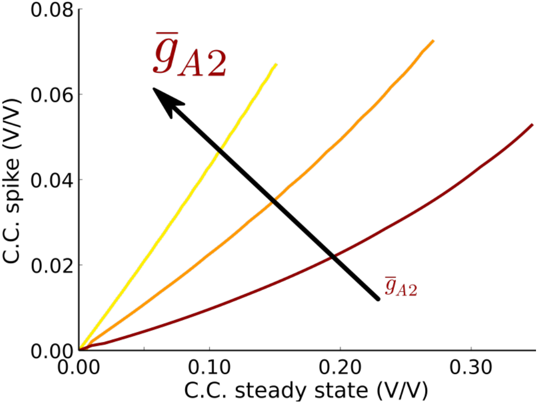
I_{NaP} doesn't change spike transmission efficacy

I_{NaP} amplified the gain of the filter in the whole frequency range: DC signals and spikes are transmitted with the same relative efficacy.



I_A improves spike transmission efficacy

According to the filter analysis, I_A increased the relative attenuation of DC signals vs faster ones. Thus, it enhances the efficacy of the transmission of spikes vs steady-state.



Conclusions

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- Spike (digital) transmission can be selectively improved by voltage-dependent resonant currents, like I_A.

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- Electrical synapses endow biological neural networks with rather sophisticated computational capabilities.
- Spike (digital) transmission can be selectively improved by voltage-dependent resonant currents, like I_A.
- Amplifying currents such as I_{NaP} boost the gain, to compensate for the attenuation caused by resonant currents.

Acknowledgments

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Thanks!

Questions?