

The Effects of Action Potential Backpropagation on Precision Coincidence Detection in MSO Neurons

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Abstract

The relationship between lateral low frequency sound localization and action potential backpropagation of MSO neurons was investigated using a simplified two compartment Hodgkin- Huxley style model. By coupling a passive somadendritic compartment to an active axonal compartment and varying parameters, different levels of backpropagation was observed. Although we found that backpropagation did not effect coincidence detection, other factors concerning dendrite nonlinearities and spiking frequencies remain to be examined.

1 Physiological Motivation

Experiments have shown that the mechanism of lateral low frequency sound localization uses interaural time difference (ITD; the time between a sound reaching either ear) to determine the position of a sound source. ITD causes the corresponding electrical signals generated by each ear reach the medial superior olive (MSO) at different times, causing neurons to spike more quickly or slowly, depending on their individual locations in the MSO and the specific situation. These spiking frequencies are then translated by other areas of the brain into the location of the sound.

We are concerned with the ability of a single, isolated MSO neuron to detect and process time differences between two inputs, not the processes of the full network of MSO neurons which help the individual locate sound. Because the efficacy of the MSO depends largely (although not entirely) on the performance of the individual cells, the behavior of one cell can be a fairly accurate indicator of the behavior of the MSO network.

The shorter the ITD, the faster the cell fires. The conversion from ITD to firing rate is called precision coincidence detection which operates on an extraordinarily fine timescale (tenths of microseconds). For humans, ITD usually does not exceed 500 microseconds because of head size. Each cell

has an ITD curve, which graphs ITD against spike output and is a good indicator of the cell's ability to perform coincidence detection.

It is important to note that an ITD of zero for the cell is probably not consistent with an ITD of zero for the individual (ie the sound reaching the left and right ear at the same time). The relationship between the individual's ITD and the cells ITD is complicated, and depends on, among other things, the location of the cell in the MSO and the system of delay lines that connect the cell to the ears.

From here on, ITD refers to the between the first input signal arriving at the cell and the second input's arrival.

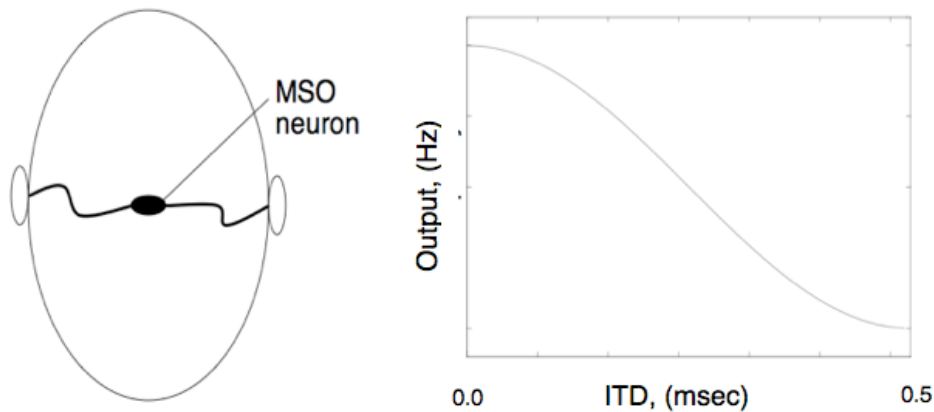


Figure 1: Left: MSO neuron inside a head. Note that the lines connecting the ears to the neuron may or may not bring the signal to the neuron in the same amount of time, meaning that ITD for the individual and ITD for the neuron are probably different. Right: Sample ITD curve for a cell.

Along with the very fine time scale of precision coincidence detection, for this project the other important characteristic of MSO neurons is their small level of action potential backpropagation. In most neurons, when a spike is produced at the axon hillock, the signal is sent down the axon to other cells and also back to the dendrites and soma. However, in MSO neurons, this signal is almost nonexistent in the soma and dendrites. [1] It is not currently known why exactly the backpropagation of MSO action potentials is suppressed, but it seems logical that efficiency of coincidence detection would be compromised if backpropagation was present.

The goal of the project was to explore the relationship between these two backpropagation and coincidence detection in MSO neurons by building a minimal Hodgkin- Huxley type model in which the level of action potential backpropagation could be controlled to elucidate its effect on coincidence detection.

2 Methods

The idea was to build the simplest possible Hodgkin- Huxley style model in which precision coincidence detection was performed and levels of back-propagation could be varied. Two compartments were used; one to perform coincidence detection and the other to produce action potentials. The somadendritic (coincidence detection) compartment is passive (ie this compartment does not have any voltage-dependent currents.) The active axonal compartment produces spikes. The two are joined by a coupling conductance in the style of Pinsky and Rinzel [2], giving the following coupled ODEs.

$$C_m \frac{dV_{sd}}{dt} = -I_{sdleak} - I_{syn}/p - I_{sdcoup}/p \quad (1)$$

$$C_m \frac{dV_a}{dt} = -I_{aleak} - I_{na} - I_k - I_{acoup}/(1-p) + I_{ns}/(1-p) \quad (2)$$

V_{sd} is the somadendritic voltage and V_a is the axonal voltage, both measured in mV . C_m is measured in $\mu F/cm^2$, and p in the percentage size of the somadendritic compartment. I_{ns} is the noise current which was modeled as standard white noise with standard deviation $2 \mu A/cm^2$.

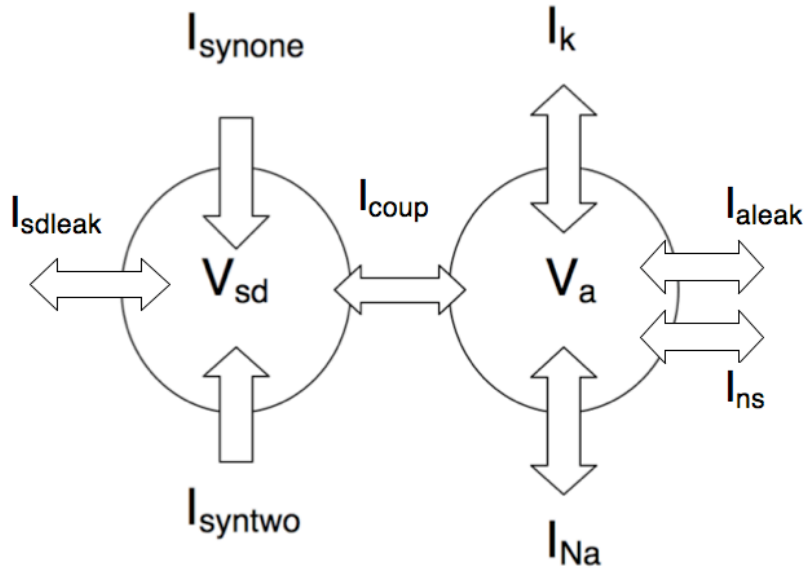


Figure 2: Diagram of the model. The somadendritic compartment receives two inputs. The axonal compartment produces spikes. The two are joined by a coupling current.

2.1 Synaptic Current

I_{syn} is modeled as such:

$$I_{syn} = g_{syn1}(V_{sd} - E_s) + g_{syn2}(V_{sd} - E_s) \quad (3)$$

Where the synaptic reversal potential $E_s=0$ mV. g_{syn1} and g_{syn2} , the synaptic conductances of the presynaptic terminals are measured in mS/cm^2 and have the following dynamics.

$$g_{syn1} = g_{mult}P_1 \quad (4)$$

$$g_{syn2} = g_{mult}P_2 \quad (5)$$

g_{mult} is a multiplier which depends on the spike threshold and other parameter values, but ranges between 1.25 and 2. P_1 and P_2 are the probabilities that a postsynaptic channel will open when presynaptic transmitter is released at their respective synapses. They are modeled as alpha functions:

$$P_i = \frac{t - t_0}{\tau_s} e^{1 - \frac{t-t_0}{\tau_s}}, t > t_0 \quad (6)$$

Where τ_s is the synaptic time constant, i is 1 or 2, corresponding to synapse 1 or 2, and t_0 is the time at which a presynaptic signal arrives.

2.2 Coupling Current

The two coupling currents are as follows:

$$I_{sdcoup} = g_c(V_{sd} - V_a) \quad (7)$$

$$I_{acoup} = g_c(V_a - V_{sd}) \quad (8)$$

Where g_c is measured in mS/cm^2 and varies from 0.1 to 50 depending on other cell parameters.

2.3 Spike Generating Currents

The sodium and potassium currents, I_{na} and I_k produce action potentials. The parameters and dynamics of these currents, as well as the leak currents I_{sdleak} and I_{aleak} , were taken from the type II cell of Rothman and Manis [3]. This sodium current is their fast sodium current. This potassium current is their high threshold potassium current.

2.4 Cell dynamics

Simulations were conducted in Matlab using the forward Euler integration scheme.

To get a better idea of how the cell functions, we show the somadendritic and axonal voltages when receiving two 100 Hz inputs of ITD zero and ITD 0.7 msec over 100 msec. (Figure 3)

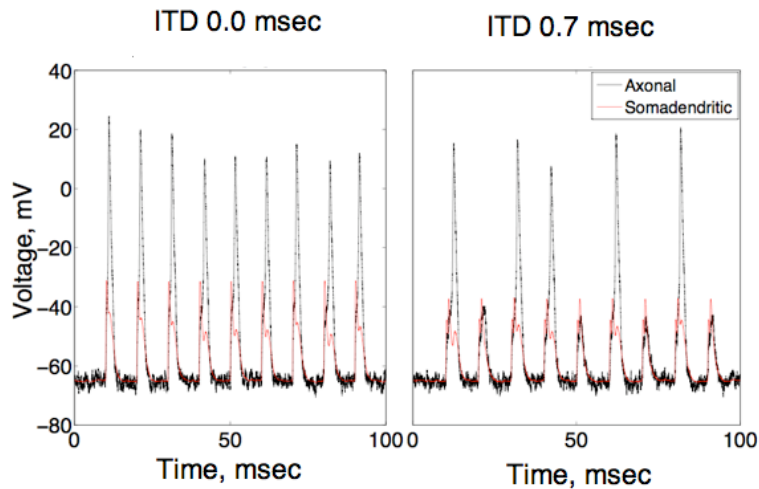


Figure 3: Sample voltage- time graphs of the two compartments. On the right, the ITD is small, so the somadendritic voltage amplitude is great enough to cause the axon to spike. On the left, the ITD is not small enough, so the axon does not spike consistently.

Notice that with zero ITD the axon spikes every ten milliseconds since the somadendritic voltage crosses the axonal threshold. However, as ITD increases, the amplitude of the change in voltage in the somadendritic compartment decreases, causing the axon to spike less frequently.

3 Results

3.1 Key Parameters

The two central parameters are p , the percentage size of the somadendritic compartment, and g_c , the conductance density of the coupling current. p controls the level to which the cell's behavior mirrors the behavior of the somadendritic compartment. The larger p is, the more the cell behaves like a single passive compartment. g_c controls the similarity of the behavior of the two compartments. As g_c grows smaller, the two compartments have less influence over one another.

To achieve the desired behavior, a balance must be found between these two parameters. The somadendritic compartment must pass on the input information to the axonal compartment via the coupling current, yet should not be so powerful that the axon is unable to spike. Nor should the axon interfere with coincidence detection in the somadendritic compartment.

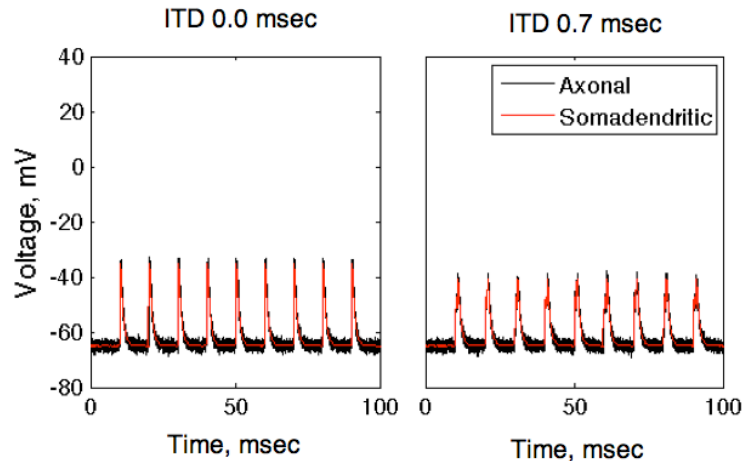


Figure 4: Voltage- time graphs with large p . The somadendritic compartment is very large, so its dynamics influence axonal dynamics. The axon does not spike, its voltage is almost identical to the somadendritic voltage.

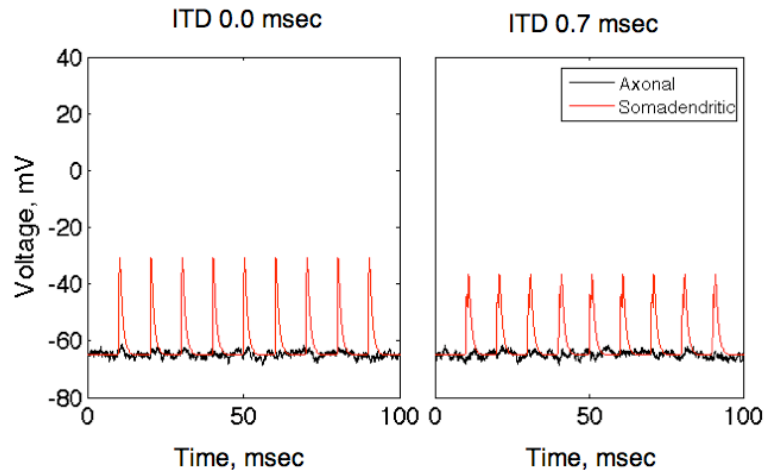


Figure 5: Voltage-time graphs with very small g_c . The two compartments behave autonomously; the axon does not spike because it receives almost no signal from the other compartment.

3.2 Backpropagation and forwardpropagation

With the sodium and potassium channels of the axonal compartment switched off, a small increase in voltage was induced in the axonal compartment. Backpropagation was measured as the amplitude of the somadendritic increase in voltage over the induced axonal shift. (So if the axonal voltage jumped 10 mV, a change of 5 mV in the somadendritic compartment would make backpropagation 0.5). Forward propagation was the axonal amplitude over the somadendritic amplitude with somadendritic voltage being initially increased.

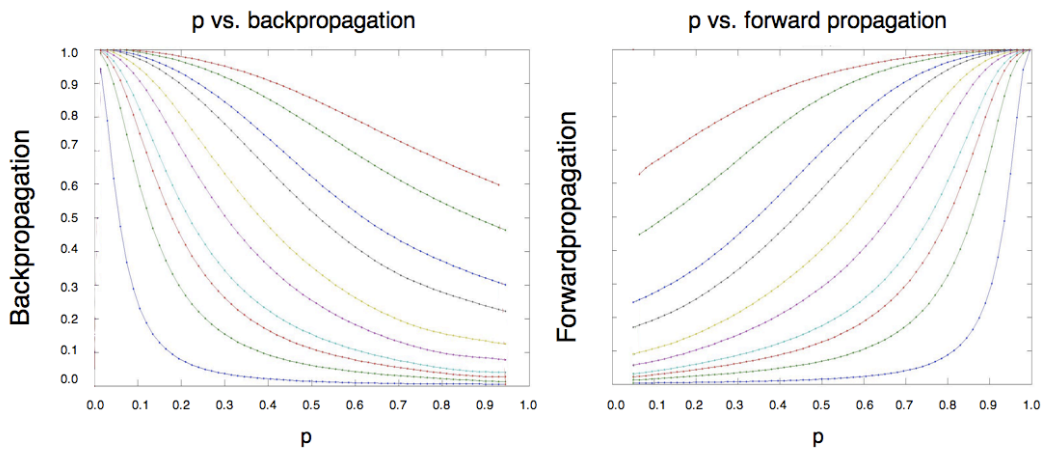


Figure 6: Forward and backpropagation vs p at different coupling conductances. $g_c = 0.1, 0.5, 1.0, 1.5, 3, 5, 10, 15, 30, 50 mS/cm^2$

After examining the relationships between, p , g_c , back and forwardpropagation, different values of p and g_c were chosen at which forwardpropagation was 0.8. Among these pairs of p and g_c , backpropagation varied from 0.18 (almost nonexistent) to 0.93 (unrealistically high). With each of these five pairs (backpropagations of 0.18, 0.31, 0.57, 0.73, 0.93), simulations were run 15 times at with ITDs ranging from 0.0 msec to 1.0 msec. Once each of the 15 trials at each ITD value were averaged, ITD curves were found for each level of backpropagation. (Figure 7) Although results were not statistically analyzed, all the five ITD curves appear to be very similar.

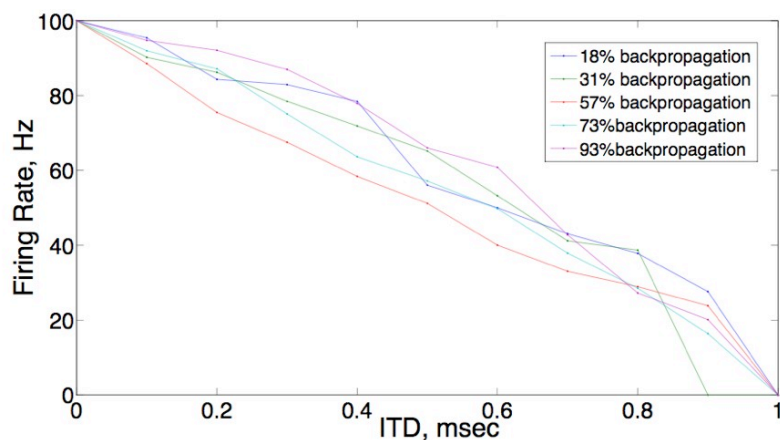


Figure 7: ITD curves for different levels of back propagation averaged over 15 trials.

4 Discussion

Because all the ITD curves are similar, these preliminary results seem to suggest that backpropagation plays no role in precision coincidence detection, but there are several factors not yet taken into account yet.

The model is probably a too minimal. The dendrites and soma are combined into one compartment which is not very realistic. Dendrites create a complicated system of delay lines which contain complex nonlinearities that might alter the mechanisms of the cell's coincidence detection.

Also, the model was not able to sustain spiking much higher than 100 Hz. This was a problem because it only took about 5 msec after a spike for the cell to return to its original state. One might expect problems to arise with a cell producing a spike from a non-resting state when considering backpropagation as well. With so much going on, information might get scrambled and ITD curves might shift.

There may be some complications with body temperature. By scaling the model differently, the cell might be able to sustain faster spiking. A new revised model remains to be constructed.

Problems with the model aside, MSO neurons have no reason to backpropagate. Other cells, like cortical pyramidal neurons, have a high levels of plasticity and need backpropagation to make appropriate synaptic adjusted. MSO neurons are believed to be hardwired, so they have no reason to actively backpropagate. That backpropagation had no effect, though it could not even hypothetically improve the cell's performance, is unconvincing.

References

- [1] Travis A. Hage Luisa L. Scott and Nace L. Golding. Weak action potential backpropagation is associated with high-frequency axonal ring capability in principal neurons of the gerbil medial superior olive. *The Journal of Physiology*, 583:647–661, September 2007.
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