Simplified neuronal model capturing brain-state specific apical-amplification, -isolation and -drive induced by calcium dynamics

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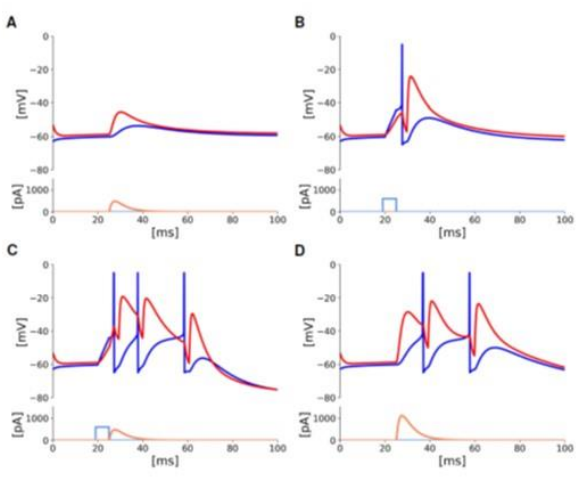
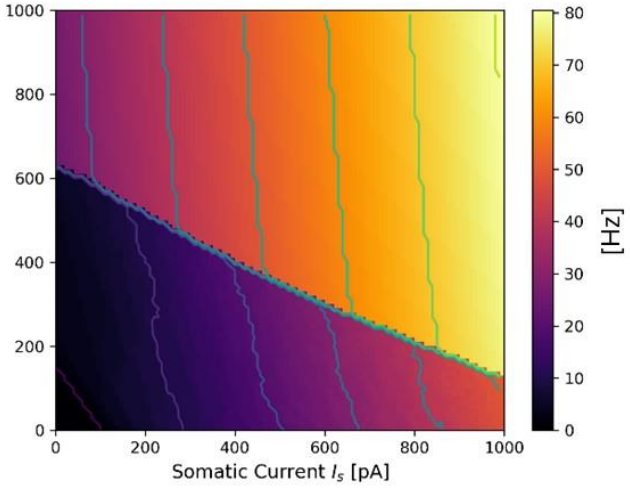
There is mounting experimental evidence that brain-state specific neural mechanisms supported by connectomic architectures serve to combine past and contextual knowledge with current, incoming flow of evidence (e.g. from sensory systems). Such mechanisms are distributed across multiple spatial and temporal scales and require dedicated support at the levels of individual neurons and synapses. A prominent feature in the neocortex is the structure of large, deep pyramidal neurons which show a peculiar separation between an apical dendritic compartment and a basal dentritic/peri-somatic compartment, with distinctive patterns of incoming connections and brain-state specific activation mechanisms, namely apical-amplification, -isolation and -drive associated to the wakefulness, deeper NREM sleep stages and REM sleep. The cognitive roles of apical mechanisms have been demonstrated in behaving animals. In contrast, classical models of learning spiking networks are based on single compartment neurons that miss the description of mechanisms combining apical and basal/somatic information. This work leverages the NEST multi-compartment modelling framework aiming to provide the NEST community with a simplified neuronal model (Ca-AdEx) that captures brain-state specific apical-amplification, -isolation and -drive through the integration of calcium dynamics in a distal compartment. The proposed neuronal model is essential for supporting brain-state specific features in NEST learning networks at minimal computational cost in the case of two-compartment Ca-AdEx usage. A machine learning algorithm, constrained by a set of fitness functions, selected the parameters defining neurons expressing the desired apical mechanisms. Furthermore, we identified a piece-wise linear transfer function (ThetaPlanes) to be used in large scale bio-inspired artificial intelligence systems.

Keywords: spiking networks, apical mechanisms, brain-states, multi-compartment neuron model, evolutionary algorithm, learning, sleep, adaptive exponential integrate-and-fire neuron model

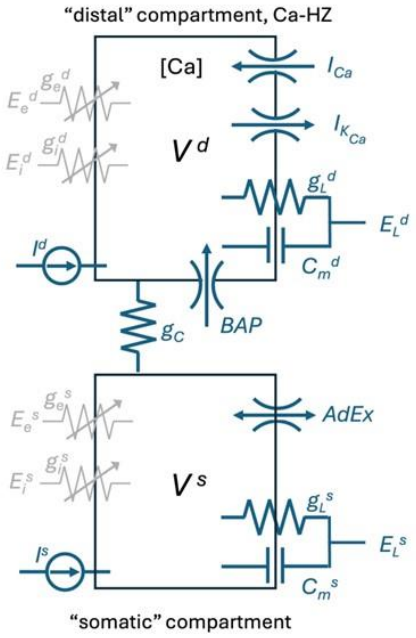


Apical amplification: the combination of a threshold somatic current as in B) and an under-threshold distal current as in A) activates the BAC firing mechanism and evokes a burst of three APs (soma in blue, distal in red) in C



Firing rate (Hz) response to apical and somatic input currents $\nu(I_s,I_d)$: somatic input on the horizontal axis, distal input on the vertical axis

$$
\begin{cases}
\begin{cases}
C_m^s \frac{dV^s}{dt} &= -g_L^s(V^s - E_L^s) + g_L^s \Delta_T \exp\left(\frac{V^s - V_{th}^s}{\Delta_T}\right) + \\
&\quad -g_e^s(t)(V^s - E_e^s) - g_i^s(t)(V^s - E_i^s) + \\
&\quad -w + I_e^s - g_C(V^s - V^d) \\
\tau_w \frac{dw}{dt} &= a(V^s - E_L^s) + b\sum_k \delta(t - t_k) - w
\end{cases} \\
\begin{cases}
C_m^d \frac{dV^d}{dt} &= -g_L^d(V^d - E_L^d) - g_e^d(t)(V^d - E_e^d) - g_i^d(t)(V^d - E_i^d) + \\
&\quad + I_{Ca} + I_{K_{Ca}} + w_{BAP}\sum_k \delta(t - (t_k + d_{BAP})) + \\
&\quad + I_e^d + g_C(V^d - V^s) \\
\frac{d[Ca]}{dt} &= \phi_{Ca} I_{Ca} + \frac{[Ca] - [Ca]_0}{\tau_{Ca}}
\end{cases}
\end{cases}
$$



Two-compartment neuron: equations and schematic representation of the somatic and distal compartments.

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Acknowledgments

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