

Distinctive Roles for Dendrites in Neuronal Computation

By John Rinzel

Neurons have been classified by their firing properties and by their differing dendritic characteristics, architectures, and biophysical properties, suggesting the existence of design principles and computational goals.

From a classical viewpoint, dendrites provide the pathways that funnel the many subthreshold postsynaptic potentials (PSPs) toward the soma, where the propagated–summed result determines if/when the neuron will spike. The theoretical groundwork for assessing dendritic function was laid by Wilfrid Rall [3,7], starting in the 1950s. Applications of the theory and computational methods for modeling membrane potential, $v(x,t)$, in dendrites have provided many key insights into, and raised new possibilities for, their functional properties, including back-propagating (soma-generated) spikes, local computations in dendrites, spike generation in spines and shafts of dendrites, and bistable dynamics [4].

Of historical note, Rall’s dendritic (linear) cable theory confronted and helped to disavow a widely touted notion: that inputs to distal dendrites were so electrically distant from the soma that they could be ignored. In those early days, when measurements were limited to somatic recordings, Rall’s theory was important for properly interpreting the recordings, for estimating cable lengths and propagation and summation characteristics of subthreshold PSPs, and for heightening awareness of dendritic computations. Today, activity can be monitored directly within the dendrites of some neurons. The very active interplay between ongoing experiments and computational work continues to uncover fascinating and powerful features of dendritic processing.

The ‘60s Revolution and Revelations

Can one solve analytically the partial differential equation of linear cable theory that describes the dynamics of dendritic integration in branching architectures? Yes, in some cases [3,7]. Elegantly formulated idealizations, a Rall signature, were key. For dendritic trees that approximately satisfy impedance matching at branch points, a single “equivalent” unbranched cable model was useful for addressing some questions (Figure 1). This simplified model,

$$v_t = v_{xx} - v + I_{syn}, \quad 0 \leq x \leq L \text{ with boundary conditions,}$$

could be solved for subthreshold (“passive”) properties, using techniques from mathematical physics, thereby providing estimates for the dendrites’ electrical length, for attenuation factors, etc. For modeling arbitrary spatiotemporal input patterns (and allowing for nonlinear membrane properties), specific cases/examples are typically explored numerically (see, however, the Rall/Rinzel papers in [7] and cited in [3]). Rall’s “compartmental” approach of spatially discretizing the cable into chains of short segments was a key development, replacing the partial differential equation with a (potentially large) system of dynamical ordinary differential equations. The compartmental method is widely used these days in computational modeling of actual dendritic structures, through digital reconstruction of stained, frozen, and thinly sliced neurons obtained experimentally [3,7].

Because of the extended structure of a dendritic tree, different spatiotemporal synaptic input patterns can have different effects on the probability for firing. This sensitivity to spatial and temporal arrangements could allow for computation of directional selectivity (as in, say, motion detection) at the neuronal level. Early on (1964), Rall showed that a train of excitatory inputs could theoretically promote firing, or not, depending on whether the inputs were delivered sequentially from distal toward somatic sites or in the reverse direction (Figure 2). It was further shown with models that the canceling effect of inhibitory inputs is greater if they occur along the direct path of an excitatory PSP as it propagates toward the soma. Various such considerations figure in the current debate about mechanisms for specific neuronal systems that show directional selectivity [4].

Figure 2. Dendritic mechanism for directional selectivity. Centrifugal (spatiotemporal) sequencing of inputs leads to slower accumulating but larger-amplitude response, which could fire the neuron—the “preferred direction.” A centripetal pattern could represent the “null direction,” with a response that might be subthreshold. Rall (1964); see [3,4,7]. (Figure adapted from [4].)

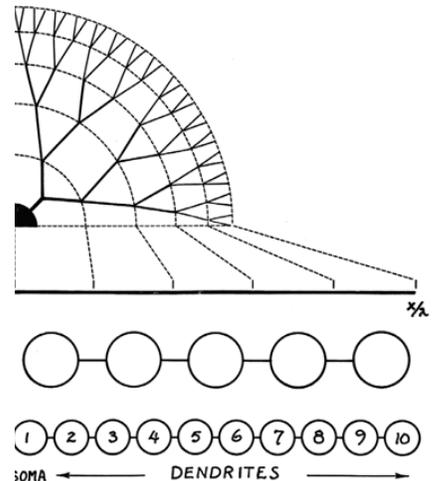


Figure 1. Rall’s reduction of a branching dendritic tree to an equivalent cylinder, assuming identical inputs at equal distance from the soma and branching that satisfies $d_o^{3/2} = \sum d_i^{3/2}$, where d_o, d_i are the diameters of parent and daughter branches. From Rall (1964); see [7].

A stunning suggestion—that dendrites could send as well as receive signals—came out of dendritic cable modeling in the analysis of extracellular recordings from multiple depths in an olfactory processing center. To account for the observed time courses, Rall and Shepherd [5] proposed that two known neuronal populations (excitatory and inhibitory) could communicate via direct synapses between their dendrites, without involving axonal propagation. At the time, the notion of dendrodendritic synapses was considered nearly heretical. Synergy for the theoretical insights came from

simultaneously discovered anatomical evidence for these dendrodendritic synapses. The modeling paper sparked, with several gems of theory: reciprocal excitatory and inhibitory synapses at the same location, a new mechanism for lateral inhibition, the importance (or not) of back-propagating action potentials, among others. Segev [6] and I agree, the paper is inspirational for its depth, idealization, artistry, and originality.

Dendrites Can Enhance Coincidence Detection

A case study from the auditory brain stem illustrates how a particular dendritic architecture and synaptic input distribution can underlie a specific computational role for dendrites.

The first neurons in the auditory pathway that receive bilateral inputs have bipolar dendrites, with each dendritic tree getting input from only one ear. These neurons perform coincidence detection with incredible temporal resolution (in the sub-millisecond range) in their role of computing interaural arrival time difference (ITD), a cue for sound localization.

In our modeling study [1] we found enhanced sensitivity to ITD when inputs from the two ears are segregated to different dendrites, rather than, say, being on the soma (or all on just one dendrite). Our explanation harkens back to a general property [3,7]: The summation of sizable synaptic inputs is generally nonlinear—that is, the input currents from nearby synapses add less than linearly. Because $I_{syn} = g_{syn}(v - v_{syn})$, the current generated by a synaptic input conductance $g_{syn}(t)$ is reduced as v gets closer to v_{syn} ; if, for example, g_{syn} is doubled, v tends toward v_{syn} but I_{syn} is less than doubled. The neuron might fire if bilateral inputs occur on different dendrites (meaning less nonlinear reduction), whereas putting the inputs on the same dendrite might preclude firing (Figure 3). Hence, the segregation of inputs to different dendrites and sublinear effects combine to reduce the likelihood of firing to inputs (for, say, a pure tone stimulus) from just one ear, thereby reducing false positives in these coincidence-detecting neurons. We further applied the model to argue that, as in some birds, across this neuronal population dendritic length correlates with the sound frequency band as selected by the cochlear filter and delivered via the auditory nerve (neurons with shorter dendrites receive input from higher-frequency sounds).

Recording from these neurons' dendrites, although difficult, is now under way. The models are being tested and are evolving to accommodate very recent discoveries on sound localization and ITD sensitivity that challenge the classical conceptual model (of Jeffress) for sound localization [2].

References

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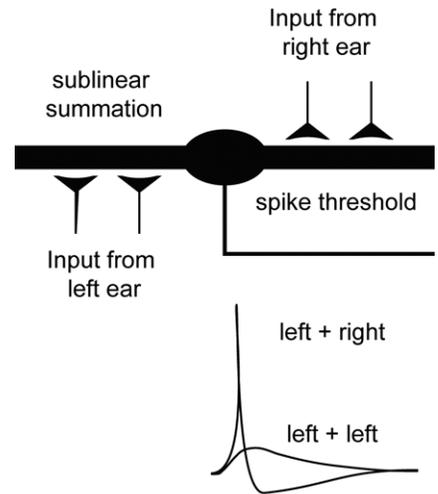


Figure 3. Detection of coincident inputs is facilitated when inputs are on separate dendrites. If all inputs came to one dendrite, the summation would be sublinear and the neuron might not fire. Agmon-Snir et al. (1998); see [1,3,4]. (Figure adapted from [4].)