Sound grounds for computing dendrites

Idan Segev

Dendrites are projections that typically originate from the cell body of neurons and are the main site for incoming synaptic inputs. Their function is largely unknown. But there is now clear-cut evidence that, in the auditory brain stem, dendrites enrich the computational power of neurons.

Why is the brain built not from spherical neurons, but from neurons that bear elaborate dendritic trees? These exquisite structures have a different morphology in different parts of the brain (Fig. 1); they are the main receptive region for synaptic inputs from other neurons and (in the periphery) they receive direct input from the sensory system involved. We have long been acquainted with the many faces of dendrites, and with new optical techniques have started to probe into the details of their physiology[1,2].

But not much is known about what dendrites actually do. Are they just to enable the connection of synaptic inputs, or simply the result of structural constraints? Are they mere chemical compartments in which very local changes in the efficiency of synapses take place? Or might dendrites also carry out some specific computation that would otherwise be hard, or less efficient, to perform — in short, can dendrites enrich the computational power of neurons? On page 268 of this issue[3], Agmon-Snir *et al.* show that they can indeed. Using the rare example of the dendrites of coincidence detector (CD) cells in the auditory brain stem, they show that, together with their synaptic architecture, these dendrites are designed for improving sound localization.

There are several reasons why CD cells provide a unique system for exploring fundamental, yet largely open, questions about the computational abilities of dendrites. First, it is known that these cells detect interaural time differences — that is, the different time that sound takes to reach the two ears, which allows the location of the sound to be identified. Second, the morphology of these cells and their synaptic connectivity are well characterized. They have bipolar dendrites, namely, dendrites that emerge from opposite poles of the cell body (Fig. 2, overleaf); and most importantly, inputs from each ear selectively contact only one dendrite. Third, the electrical properties of these cells and their response to input sound are understood.

In an experimentally based biophysical model, Agmon-Snir *et al.* have succeeded in identifying the principles that underlie the improvement of coincidence detection by dendrites. Moreover, they provide a novel explanation for an interesting experimental finding — that the CD cells sensitive to lower-frequency sounds have longer dendrites than do high-frequency CD cells.

An auditory CD neuron performs its job successfully if it fires maximally when, after compensation for interaural time differences by delays within the nervous system, the inputs it receives from the two ears coincide in time. It should fire less when the inputs arise from only one ear, even if those inputs are doubled. With a linear system, these two possibilities cannot be distinguished; what is required is some nonlinear mechanism that dampens the auditory input when it arrives from only one ear but not when it arrives from both ears.

The improvement of coincidence detection (and thus of sound localization) by the CD neurons exploits a fundamental biophysical mechanism — the nonlinear summation, or saturation, of excitatory synaptic inputs and, specifically, the exaggeration of this nonlinear loss when the inputs are spatially clustered on one dendrite rather than distributed between several of them[4]. Theoretical studies show that when synaptic inputs are activated close together — that is, on the same dendrite — the local voltage change in this dendrite is larger, and the reduction in the driving force for the synaptic current is more pronounced, than when the synapses contact different parts of the dendritic tree (that is, two different dendrites). In this second case, more depolarizing current is generated by the synapses and a spike is more likely to be generated in the axon leaving the cell body (Fig. 2), signalling that the sound is coming from a particular location.

All in all, designers of CD neurons who really understand the biophysics of synapses on dendrites will use neurons with bipolar dendrites, rather than spherical neurons. They will then make sure that inputs from each ear terminate on different dendrites.

But those designers also have to avoid over-using the mechanism of nonlinear synaptic addition, because saturation can also lead to loss of performance. When

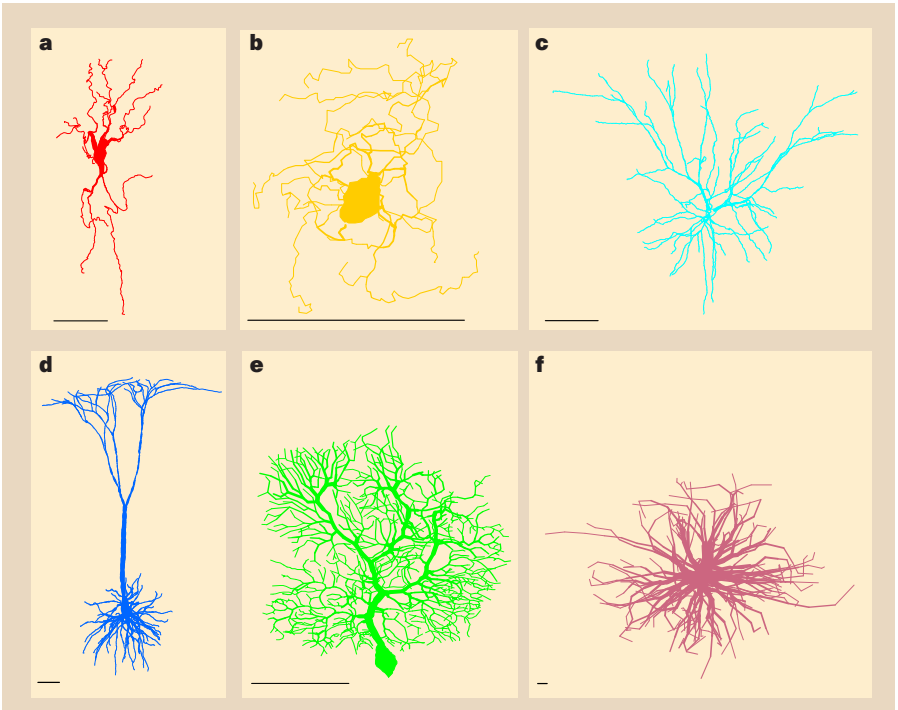

Figure 1 **Dendrite variety. Neurons with dendritic trees exist in all sorts of shapes and sizes depending on which region of the brain they come from. Shown here are the dendritic trees of:** a, **a vagal motorneuron;** b, **an olivary neuron;** c, **a layer 2/3 pyramidal cell;** d, **a layer 5 pyramidal cell;** e, **a Purkinje cell; and** f, **an α-motorneuron. Scale bars, 100 μm.**

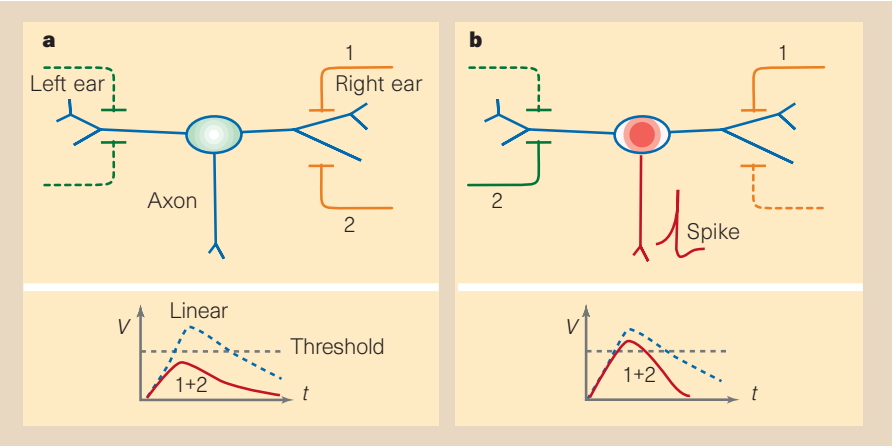

Figure 2 **How the bipolar dendrites of coincidence detection neurons, and the mapping of synaptic inputs from each ear to different dendrites, improve sound localization. That improvement is achieved using the nonlinear mechanism (saturation) inherent in the summation of excitatory synaptic inputs, and the exaggeration of this nonlinear loss when the inputs are clustered on one dendrite.** a, **When the input arrives from only one ear, reaching only one dendrite, the consequence of nonlinear summation in that dendrite is that less depolarizing synaptic current is generated. The resulting synaptic potential is too small to generate spike firing in the output axon.** b, **When inputs arrive simultaneously from the two ears and are segregated on different dendrites, nonlinearity in the summation of the synaptic inputs is less significant. The resulting synaptic potential is above the threshold and it gives rise to a spike being fired in the axon.**

inputs from one ear are likely to saturate the dendritic potential, a mistimed input from the other ear (to another, unsaturated, dendrite) becomes very effective in depolarizing the axon and may result in an inappropriate firing of the cell. Indeed, with increasing sound frequency, the task of phase-locking between the input sound and the timing of spikes in the auditory nerve is more difficult and the precision of spike timing falls off (that is, the spikes 'jitter'). One way to counteract the possibility of erroneous CD firings is to reduce saturation at the dendrites in high-frequency CD cells, which can be done by making the dendrites shorter. With shorter dendrites, a lower voltage is required at the synaptic site for triggering a spike in the output axon. That is because less current is lost to the other dendrite and more is available to reach the threshold for spike firing; the lower the dendritic voltage, the smaller the saturation at the dendritic site. Obviously, the benefits of nonlinear addition are less for shorter dendrites. So Agmon-Snir and colleagues' model predicts an optimal length for a given frequency, with shorter dendrites for higher frequencies, and experiments[5] show that this is indeed the case.

What of other types of neuron with dendrites, such as those depicted in Fig. 1 — do they use similar principles to enrich their computational capabilities? The example provided by Agmon-Snir *et al.* is a rare one, because we usually don't know the specific computational function of a given type of neuron. So the modelling studies of the past 30 years need pushing further to continue to provide insights into the possible computational power of neurons with dendrites (for reviews see refs 6–10). The new work[3] was inspired by these studies, and it is likely that the computational module isolated in the auditory neurons for improving coincidence detection might be used in other dendritic neurons with input segregation, such as cortical pyramidal neurons and cerebellar Purkinje cells, perhaps as part of a more complex computational system.

But the findings of Agmon-Snir *et al.* go beyond providing one convincing example of dendritic function, for they also bear on a controversy between two schools of thought. These are the 'individualists', who believe in the functional primacy of the neuronal details (the specific dynamics of synapses, the fine morphology of the dendrites, the exact timing of spikes); and the 'socialists', or 'connectionists', who believe that the characteristics of neuronal society owe little to the properties of its individual components. Agmon-Snir *et al.* have demonstrated the power of the individual, but we eagerly await more studies that tie the variety of dendritic morphologies to their specific function. □

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Climate change

The carbon equation

David S. Schimel

Following the signing of the Climate Convention in Rio in 1992, and the subsequent conference in Kyoto late last year, there is a pressing need to find out more about the relationship between anthropogenic emissions of the main greenhouse gas, CO_2, and the resulting atmospheric concentrations. In its reports[1,2] dealing with 1994 and 1995, the Intergovernmental Panel on Climate Change (IPCC) provided estimates for a wide variety of scenarios, to give policymakers some information on anthropogenic emissions consistent with the aim of stabilizing atmospheric CO_2 at a range of levels (from 350 to 1,000 parts per million by volume).

Uptake or release of CO_2 from the world's oceans and terrestrial ecosystems is central to understanding the relationship between emissions of CO_2 and its atmospheric levels. The IPCC 1994 assessment, however, conducted only a preliminary examination of how altered CO_2, climate and ocean circulation might affect that relationship. Now, in papers on pages 245 and 249 of this issue, Sarmiento *et al.*[3] and Cao and Woodward[4] provide model-based clues to the effects of environmental change on CO_2 fluxes in the oceans and on land. These studies point to substantial differences in the fluxes compared with the estimates used as base cases in the IPCC reports.

Cao and Woodward[4] suggest that the terrestrial biosphere could act as a significant sink for carbon over the next century because of a large stimulation of photosynthesis by increased CO_2; that sink would, however, be reduced by increased respiratory losses of carbon with warming. The authors present the important result that the terrestrial sink must become saturated — both because photosynthesis follows a saturating function with respect to CO_2, and because, as the rate of increase in photosynthesis slows, plant and microbial respiration must catch up, eventually reducing incremental carbon storage to zero. Although Cao and Woodward's model neglects land-use change and deforestation[1,2], and nitrogen deposition[5], it