DYNAMIC RANGE OF A SENSORY NETWORK CONNECTED BY GAP JUNCTIONS

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A very common trade-off problem found in the biology of sensory mechanisms (and sensor devices in general) is the competition between two desirable goals: high sensitivity (the system ideally should be able to detect even single signal events) and large dynamic range (the system should not saturate over various orders of magnitude of input intensity). For example, in physiology broad dynamic ranges are related to the Weber-Fechner law [1]: the response R of the sensory system is proportional not to the input level I but to its logarithm, $R \propto \ln I$.

It is known that receptor cells of sensory systems are electrically coupled via gap junctions [2]. However, their functional roles are largely unknown. Here we report a simple mechanism that could increase at the same time the sensitivity and the dynamic range of a sensory epithelium by using only this electrical coupling. In this work, we used two networks (in one and in two dimensions) of biophysically plausible cell models implemented in GENESIS 2.2. For each network, an uncoupled and a coupled (via gap junctions) version was constructed. The cells were submitted to external inputs modeled by a Poisson process with variable input rate r (in the range from 0.001 $\sec^{-1}$ to 1,000 $\sec^{-1}$). For a given input rate r, the network response was measured by the average firing rate f (spikes per second per cell) over a sufficiently long time.

For the uncoupled network, in the low rate regime the activity of the system is proportional to the signal rate r. If the rate increases, there is a deviation from the linear behavior due to the cell's refractory period.

For the coupled system, single input events create activity waves that propagate along the network, leaving behind a trail of refractoriness, which prevents the appearance of new spikes immediately. More importantly, refractoriness is responsible for wave annihilation: when two wave fronts meet at a network site they get trapped because the neighboring cells have just been activated and are still in their refractory period (we are using open boundary conditions so that waves disappear at the extremes of the network). This is a well-known phenomenon in excitable media [3].

Due to a chain-reaction mechanism, the spike of a single receptor cell is able to excite all the other cells. The sensitivity per neuron thus increases in proportion to the size of the network. This is a somewhat expected effect of the coupling, since a neuron *j* is excited by signal events that arrive not at neuron *j* but elsewhere in the network.

More surprising is the fact that the dynamic range (the interval of rates where the neuron produces appreciable but still non-saturating response) also increases dramatically. This occurs due to a second effect, which we call the self-limited amplification effect. For small rates, where inputs are very separated in time from each other, a single spike of some neuron produces a response in every one of the network cells. However, for higher input rates, where a new spike occurs at neuron *k* before the wave produced by neuron *j* has disappeared, when *k* is situated beyond the front of the *j*-initiated wave both the *k* and the *j* wave fronts will run toward each other and will annihilate.

Therefore, although the amplification for small rates is very high, saturation is avoided due to the fact that the amplification factor decreases with the rate in a self-organized non-linear way. The resulting effect is to transform the individual linear-saturating curves of individual cells into a collective Weber-Fechner like logarithmic response curve with high sensitivity to single events and large dynamic range. Besides, the network response exhibits a power-law behavior (Stevens law) [4] for an interval of input rate values.

Concerning the functional role of gap junctions for signal processing, it has been recognized that they provide faster communication between cells than chemical synapses and play a role in the synchronization of cell populations [5]. The results of this investigation suggest another functional role for gap junctions, namely the enhancement of the dynamic range of neural networks.

References

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