Olfactory coding: Unusual conductances contribute to sparse neural representations.

Focus on “Intrinsic Membrane Properties and Inhibitory Synaptic Input of Kenyon Cells as Mechanisms for Sparse Coding?”

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At the interface of animal and world, neurons transform environmental stimuli into spikes of electrical current known as action potentials. As sensory information makes its way from point to point along neural pathways, the numbers of neurons participating in the response and the numbers of spikes they generate often dramatically decrease – that is, the sensory representation becomes sparse (Barlow 1972).

Sparse neural representations have been observed in many sensory systems (visual: Vinje and Gallant 2000; Weliky et al. 2003; Young and Yamane 1992; auditory: DeWeese et al. 2003; olfactory: Ito et al. 2008; Lin et al. 2006; Perez-Orive et al. 2002), and in many brain areas (Quiroga et al. 2005; Rolls and Tovee 1995; Vinje and Gallant 2000). An extreme and canonical example of sparse coding would be the hypothetical “grandmother cell,” one that responds only to a specific, complex percept or concept (see review by Gross 2002). But many degrees of sparseness are possible.

Sparseness can be measured in temporal terms as the amount of spiking in a single neuron over time (lifetime sparseness), or in spatial terms, over an ensemble of neurons, as the likelihood any given neuron will spike in a period of time (population sparseness). These two forms of sparseness need not be correlated (Willmore and Tolhurst 2001). Theoretical and computational studies suggest that sparse coding formats offer several advantages to neurons processing information (see review by Olshausen and Field 2004). From a metabolic point of view, each spike is costly: energy is required to restore ionic balances perturbed by synaptic and action potentials and for neurotransmitter release and reuptake. Signaling accounts for the majority of
energy consumed by the brain (Laughlin 2001); Lennie (2003) estimated that energy
constrains would permit fewer than 1% of human cortical neurons to fire concurrently.
And, perhaps more importantly, sparsely coded information can maximize coding
space for representations of sensory stimuli. This increases the brain’s memory
capacity, reduces the number of synapses that must be modified to stabilize learned
associations (Laurent 2002), and permits plasticity by simple local rules such as
Hebbian mechanisms (Marr 1971; Willshaw et al. 1969).

How does sparse coding arise in sensory systems? In this issue, Demmer and
Kloppenburg characterize the circuit and intrinsic mechanisms underlying sparse
coding in Kenyon cells (KCs), a particularly interesting population of neurons found
in the brains of many insects. These neurons are interesting for several reasons.
They integrate multiple modes of input. They also appear subject to modulation
from neurons bearing reward transmitters and have been linked to learning and
memory. And they appear to play a special role in olfactory coding, distilling
barrages of spiky input into specific and very sparse output. Such sparse olfactory
responses have been reported in the KCs of several species (Ito et al. 2008;
Perez-Orive et al. 2002; Szyszka et al. 2005; Wang et al. 2004), but mechanisms
responsible for this sparsening have probably been most intensively studied in the
locust. There, each of the 50,000 KCs in each brain hemisphere receives excitatory
inputs from hundreds of projection neurons (Jortner et al. 2007), each of which fires
spontaneously and can respond to odors with great bursts of spikes. Despite
receiving densely convergent active inputs from so many projection neurons,
individual KCs are nearly silent at rest, and odor responses within the population of
KCs are extremely sparse; they typically consist of very few spikes in a small subset
of the neurons (Perez-Orive et al. 2002; Stopfer et al. 2003).

In locust KCs, responses to odors are sparsened by both circuit and intrinsic properties. Odor-elicited spikes in groups of projection neurons are corralled by periodic inhibitory input from local GABAergic interneurons in the antennal lobe (Macleod and Laurent 1996) into ~20 Hz oscillatory waves of synchronized excitatory output that impinges upon the KCs. But, in addition to synapsing upon KCs, projection neurons also send branches to a small group of inhibitory cells in a structure called the lateral horn. These lateral horn interneurons, in turn, project feed-forward GABAergic outputs onto the KCs. The net effect of this circuitry is to provide the KCs with rapidly alternating cycles of input each consisting of a wave of excitation directly from projection neurons followed by a wave of inhibition from the lateral horn interneurons. Thus, each ~50 msec oscillatory cycle defines a time window for integrating input. During each cycle, a KC can briefly integrate information-bearing synaptic inputs from projection neurons before the cycle closes with a wave of inhibition from the lateral horn. This circuit function, likely with help from other inhibitory neurons, effectively sparsens odor responses in KCs; abolishing this inhibition, for example, by injecting the GABA blocker picrotoxin into the vicinity of the KCs broadened their EPSPs and reduced the odor selectivity and sparseness of their responses (Perez-Orive et al. 2002, 2004).

The KCs themselves are known to have intrinsic properties that restrict responses to the highly coincident input provided by the synchronized spiking of projection neurons (Perez-Orive et al. 2002, 2004). However, the conductances responsible for these properties are poorly understood. Working on cockroaches, Demmer and
Kloppenburg conducted a rigorous and detailed study of the intrinsic ionic properties of KCs and the influence of the inhibitory inputs they receive. Notably, instead of using cultured neurons as is common for this type of study, the authors made their recordings from acute preparations of the intact cockroach brain. This allowed the authors to examine conductances in a close-to-in vivo environment free from potential culture-induced artifact. And since much of the olfactory pathway was preserved, it was possible for the authors to investigate KCs in the context of their natural circuitry.

Demmer and Kloppenburg confirmed that the responses of cockroach KCs to odors were very sparse both in lifetime and population respects. All tested KCs could generate spikes when driven by current injection, but were otherwise nearly silent. With pharmacological blockades, ion substitutions and current subtraction techniques, the authors isolated several ionic currents in the KCs. While most of the KC conductances revealed by the authors were similar to those characterized in other insect neurons, the inward calcium (I_{Ca}), and calcium–dependent outward (I_{O(Ca)}) currents in KCs stood out as unusual. I_{Ca} had a very low activation threshold and a very high current density – properties which could non-linearly boost and sharpen EPSPs in KCs. The outward I_{O(Ca)} had an unusually high current density and an unusually depolarized activation threshold which, together with I_{Ca}, likely contributes to the strong spike frequency adaptation observed in KCs. These uncommon ionic properties likely underlie the sparsening of odor representation in populations of KCs.

The authors went on to explore the roles inhibitory inputs could play in establishing the resting potential and input resistance of KCs. They found that abolishing this input by blocking GABA_A receptors (with picrotoxin) and GABA_B receptors (with CGP 54626) raised the input resistance and resting membrane potential of KCs. The
authors concluded that tonic inhibition likely suppressed spontaneous spiking while raising the bar for odor-elicited excitatory drive to generate action potentials in KCs. It’s not yet known whether a feed-forward inhibitory circuit like that found in the locust olfactory pathway also acts to sparsen responses in the cockroach, but cockroaches do appear to use a mechanism like that of the locust for the oscillatory synchronization of olfactory neurons (Stopfer et al. 1999).

The current study provides valuable information for those seeking to understand the origins of sparse neural codes. Physiologists will find here a conductance-based mechanism for a physiological property understood in a network context. Modelers will find detailed conductance parameters. In other systems, slow-recovering Na\(^+\) channels which can prevent neurons from firing at high frequencies (Tsutsui and Oka 2002), and low voltage-activated K\(^+\) conductances (Monsivais et al. 2000) which can prevent the temporal summation of inputs, have been found to underlie sparsening of neural responses. Here, Demmer and Kloppenburg describe another potential ionic mechanism that can lead to sparse neural representations.
REFERENCES


