Principles of Neural Design 1

Design principles of sensory systems

1. Sensory receptor neurons are molecularly specialized to detect a specific physical stimulus. Molecularly distinct classes of sensory receptor neurons project separately to the brain, forming 'labeled lines' to sense different types of stimuli.

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2. Downstream of sensory neurons, spikes carry information[1].

[1] Except for some cells in retina, which use subthreshold potentials.

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2. Downstream of sensory neurons, spikes carry information[1].
3. Real-world sensory information is not encoded by the spiking of a single neuron, but by populations of neurons. This is termed population coding. A neural code is a specific pattern of spikes occurring in a specific set of neurons.

Forms of neural coding

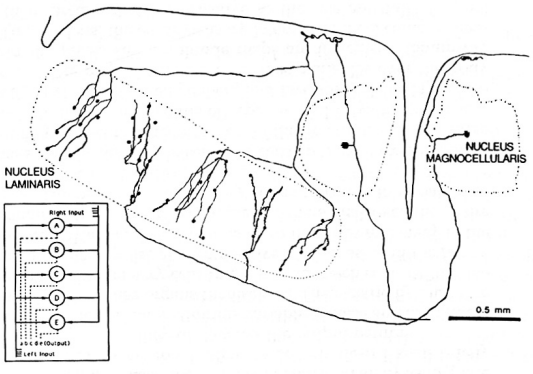
Place code. Stimulus identity encoded by location of active cells within a topographic map.
Rate code. Stimulus intensity coded by firing rate of active neurons.
Temporal code. Stimulus identity encoded by precise timing of spikes in a population of neurons.
Dense code. Stimulus information is encoded by spiking within a large population of neurons in a brain area.
Sparse code. Stimulus information is encoded by spiking of only a small fraction of neurons in a brain area.

Principles of Neural Design 1

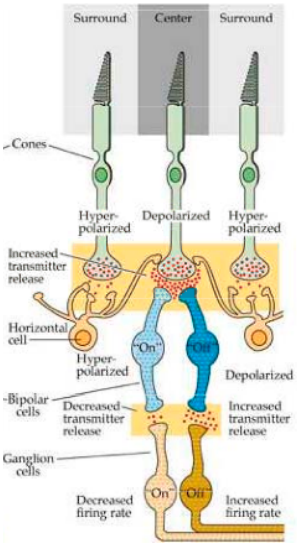
Design principles of sensory systems

4. Local microcircuits perform specific computations, based on circuit connectivity and synapse/cellular properties, including integration of excitation and inhibition.

ITD calculation in nucleus laminaris



Center-surround receptive field synthesis in retina



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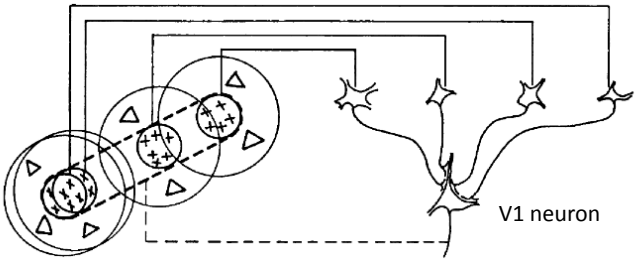
Synthesis of orientation tuning in V1

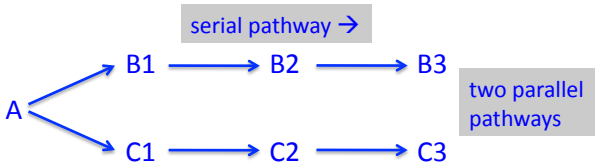


Hubel & Wiesel

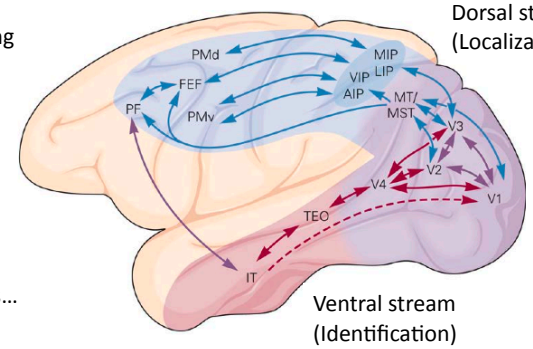
Parallel and serial pathways

Design principles of sensory systems

5. Information flows in parallel pathways and serial pathways across brain areas.



Visual processing pathways



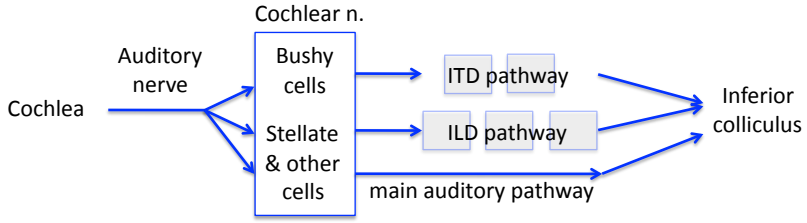
Dorsal stream (Localization)

Other examples…

Ventral stream (Identification)

Advantages of parallel pathways

Another example of parallel pathways. What is the advantage of parallel pathways?



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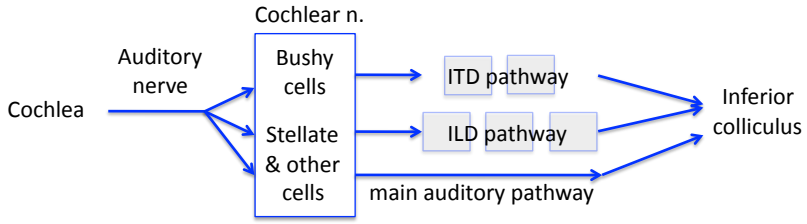
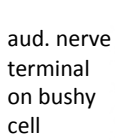
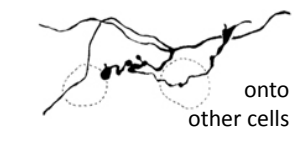
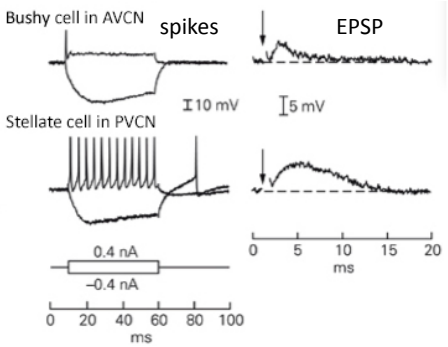




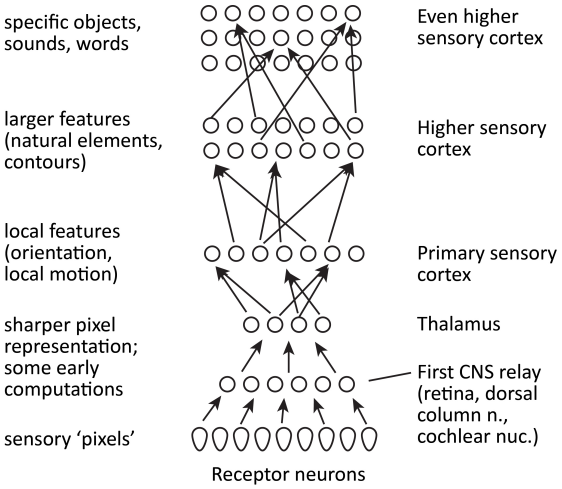




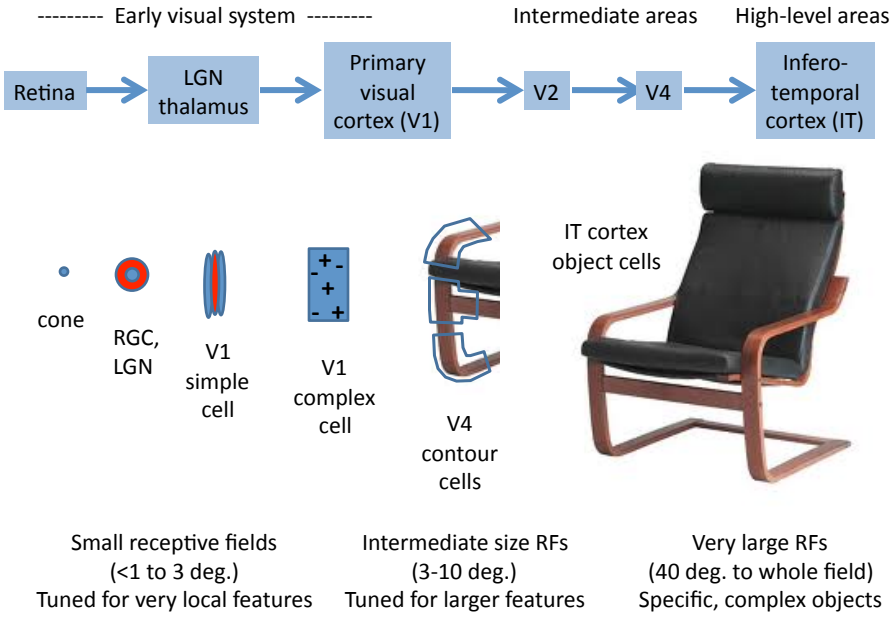
Serial pathways for sensory processing

Design principles of sensory systems

6. Serial pathways process information in small, incremental steps, which ultimately generate complex tuning properties.



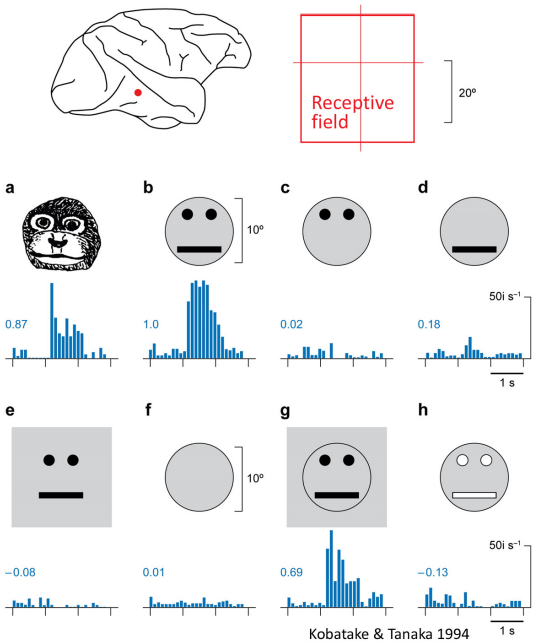
Serial pathways for sensory processing



Neurons tuned to specific, complex stimuli

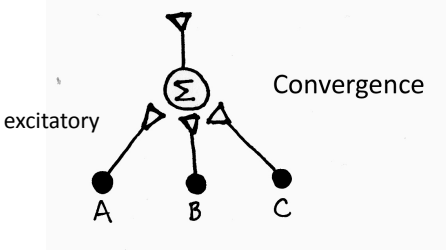
How do face cells recognize a face?

They don't detect one unique feature. Instead they seem **to integrate across multiple features** that are characteristic of faces.



Kobatake & Tanaka 1994

A common microcircuit can integrate sensory features



This circuit can have two functions:

Makes neurons sensitive to conjunction of A, B, and C if spike threshold >> single EPSP.

or

Makes neurons sensitive to either A, B, or C if spike threshold ≈ single EPSP.

Serial pathways for sensory processing

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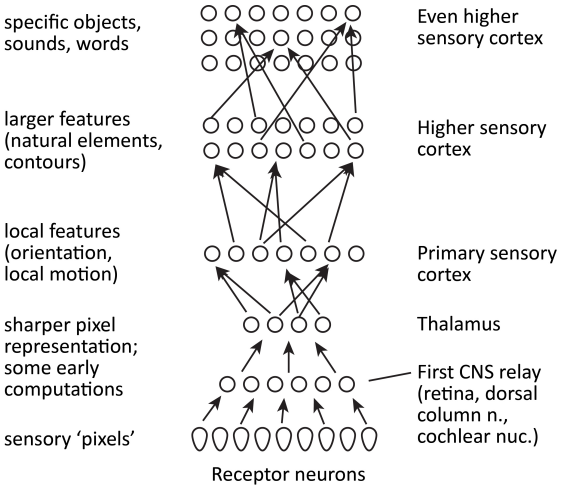
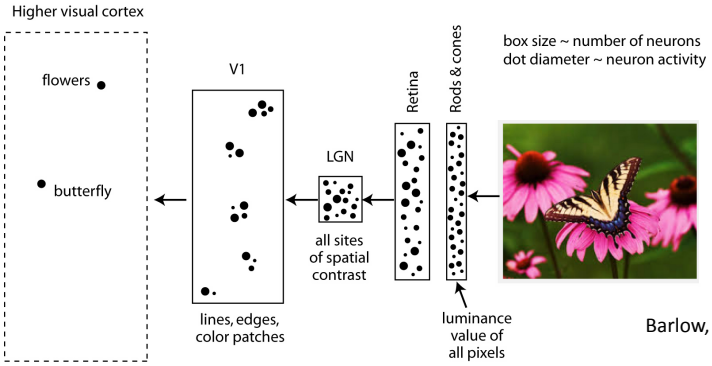


Sparse sensory coding

Design principles of sensory systems

7. Higher brain areas represent information with sparse neural codes.

Low-level sensory areas contain neurons activated by common stimulus features, while high-level neurons are often tuned for specific, whole, real-world stimuli. Thus, neural activity will be **sparser** at higher sensory levels.



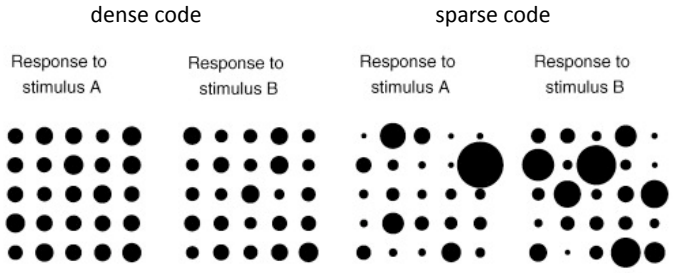
Barlow, 1972

Sparse coding. 1) Representation of the sensory world or other information with **relatively few active neurons**, and **relatively few action potentials**.

Sparse sensory coding

In a sparse population code, neurons have narrow tuning, and a small fraction of neurons spike to any one stimulus. Two stimuli activity different, non-overlapping sets of neurons.

In a dense population code, neurons are broadly tuned, and many are active at once. Two stimuli activate overlapping sets of neurons, with only subtle differences in the firing rate of different neurons.



Hromadka & Zador, 2009

Advantages of sparse coding

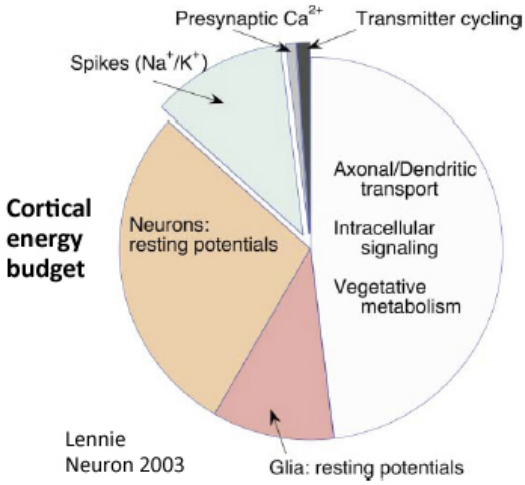
1. Sparse population codes represent sensory stimuli simply by the identity of which neurons are firing.

2. Two stimuli can be distinguished more easily using a sparse code than a dense code.

Why not use an extremely sparse code, with each stimulus encoded by the spiking of one, unique cell? Grandmother cell hypothesis. This would present problems—e.g., sensitivity to cell loss, or to noise (spontaneous activity).

Advantages of sparse coding

3. Spikes cost ATP, so any code with few spikes saves energy.



Cerebral cortex
475 g
3.4×10^{21} ATP/min

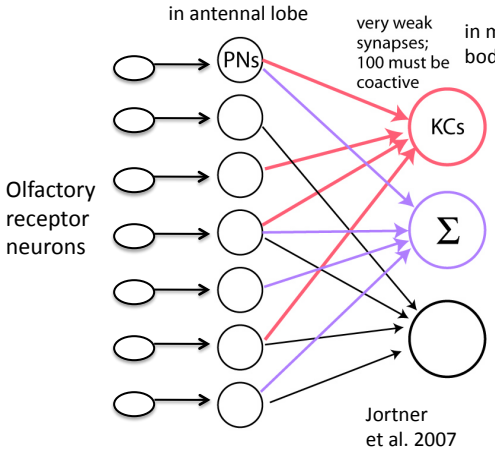
13% of ATP is spent on spikes and associated PSPs.

The ATP available to the Na/K pump can only support a mean discharge of 0.16 Hz / neuron.

This corresponds to 1-4% of neurons being active (50 Hz, 10 spikes) at any one time.

Example of sparse coding: insect olfaction

Olfactory receptor neurons → Projection neurons (PNs) → Kenyon Cells (KCs)
Olfactory receptor neurons and projection neurons code the olfactory world with a dense code. KCs are activated only by very specific odor combinations, and use a very sparse code.



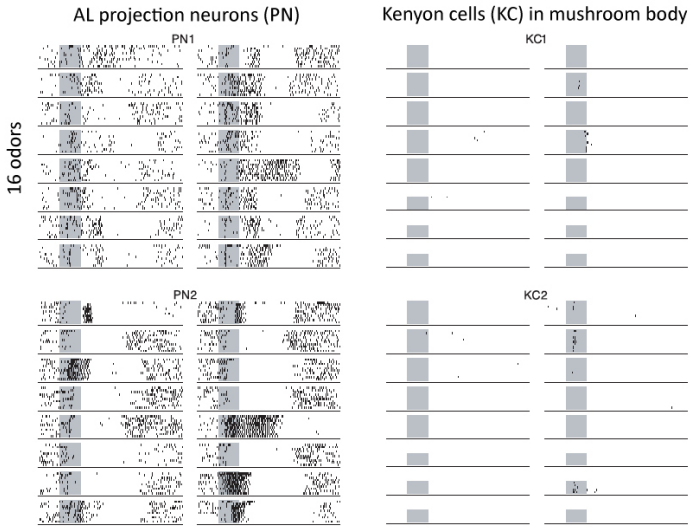
Each PN spikes to many odors.

Each KC receives input from a random set of 100+ PNs.

Each KC spikes to the small set of natural odors that activate > 100 of its input PNs.

Example of sparse coding: insect olfaction

Transformation from dense code to sparse code in PN → KC projection

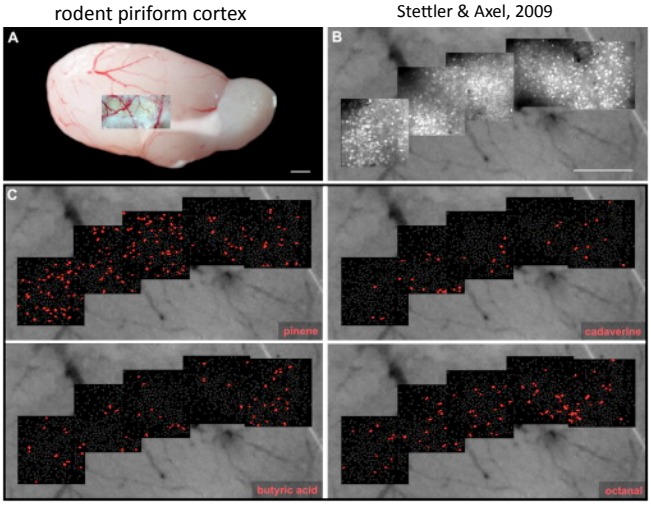


Sparse coding in sensory cortex

Different odors activate different, sparse cell populations in piriform (olfactory) cortex.

rodent piriform cortex

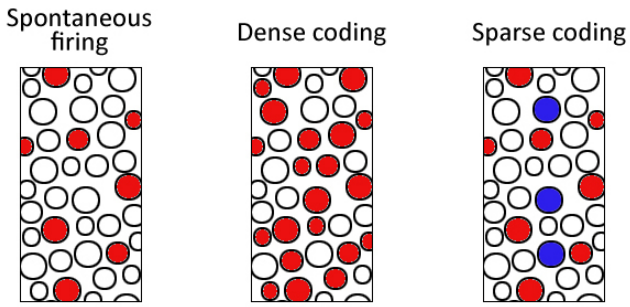
Stettler & Axel, 2009



Ca imaging in vivo, 4 odors

Sparse coding in sensory cortex

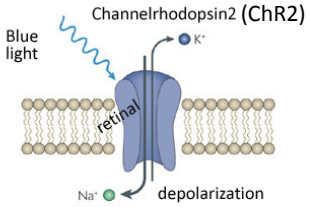
In rodent somatosensory cortex, each cortical column contains 10,000 neurons.
A weak sensory stimulus drives 1-2 spikes each in maybe 100 neurons.

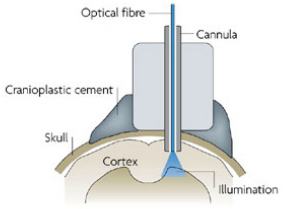


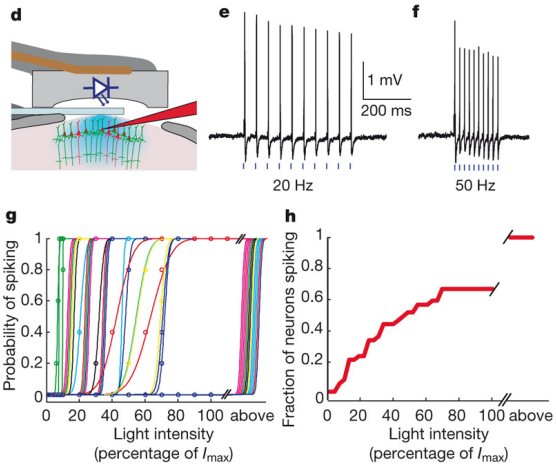
A challenge of sparse codes: How can the brain detect this small amount of spiking activity, given ongoing spontaneous firing in the network?

How many action potentials are required for perception?

Express ChR2 in L2/3 pyramidal cells

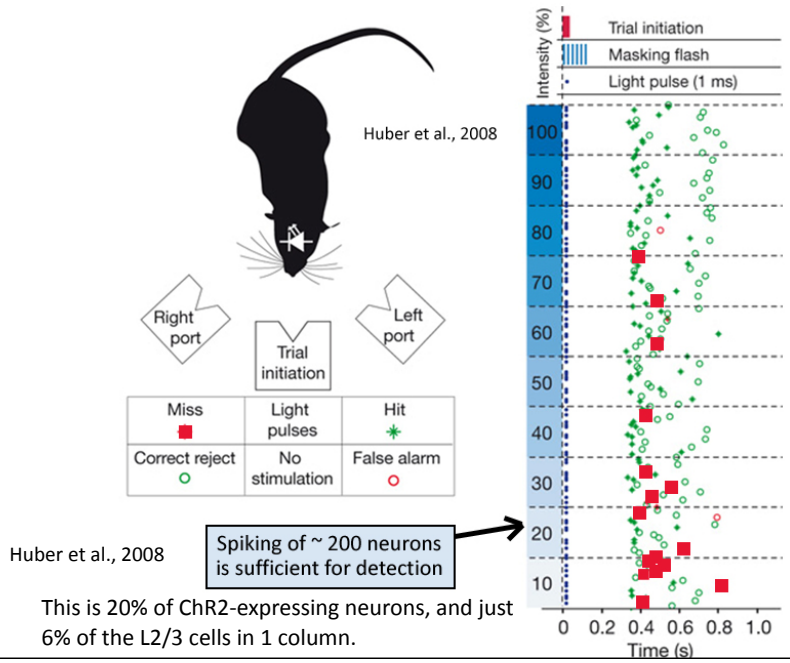






Huber et al., 2008

How many action potentials are required for perception?



Huber et al., 2008

Spiking of ~ 200 neurons is sufficient for detection

This is 20% of ChR2-expressing neurons, and just 6% of the L2/3 cells in 1 column.

Conclusions: Sparse Coding

Design principles of sensory systems

7. Higher brain areas represent information with sparse neural codes.

The brain generates sparse codes with small populations of neurons tuned for specific natural stimuli.

This enables more efficient processing, and conserves ATP.

The brain can read sparse codes despite spontaneous activity, and can detect as few as ~ 200 neurons spiking.