

Receptive Fields 1

From Sherrington to Place Cells

Neurophysiology and Behavior, Drew B. Headley, Spring 2021

What you should know after this lecture

- The history of receptive field analysis.
- How to identify and interpret a receptive field experiment.
- Familiarity with the most common types of receptive fields.

The goal of this lecture is to survey the most common receptive fields across various sensory modalities.

What we will cover:

A tour of receptive fields (RFs, aka 'Tuning Curves')

- The RF as a concept
- Visual cortex RFs
- Auditory cortex RFs
- Somatosensory cortex RFs
- Olfactory cortex RFs
- Hippocampal RFs
- General principles of RF

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First use of 'receptive field'

Sherrington, 1906

VII. THE RECEPTIVE FIELD.

The whole area of skin from whose points the scratch-reflex can be elicited may be conveniently termed the *receptive field* of that reflex (Fig. 19). The receptive field may be considered as composed of receptive points. That is to say, what is referred to as 'the scratch-reflex' in general is strictly speaking a group of reflexes all more or less alike, all using broadly speaking the same motor apparatus in broadly speaking the same way. And this group of individual reflexes forms a physiological group not only on account of their general similarity but also because they act harmoniously upon the same efferent path, and, in many instances at least, demonstrably reinforce each other's action on that

'Receptive field' as a term did not start with sensory physiology, but instead reflex physiology. Charles Scott Sherrington, a famed neurophysiologist that studied the integrative properties of the nervous system, coined the term in his paper *Observations on the scratch-reflex in the spinal dog* in 1906. This paper was a thorough exploration of touch induced scratching in dogs.

The receptive field was the patch of skin that when stimulated electrically elicited a scratching response.

First use of 'receptive field'

Sherrington, 1906

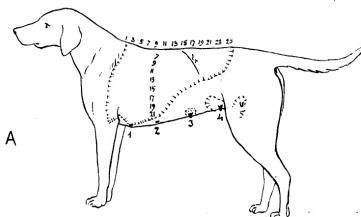
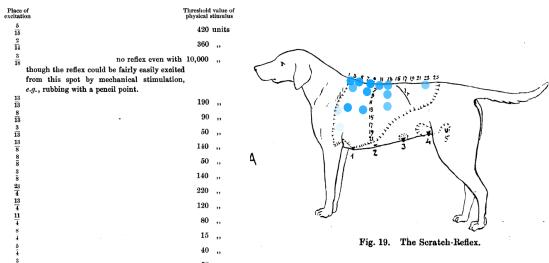


Fig. 19. The Scratch-Reflex.

Early studies, such as Sherrington's, tended to only present exemplar cases that illustrated a particular point. In this case, a single dog is displayed and a grid is defined across its skin to indicate where the stimulation was delivered.

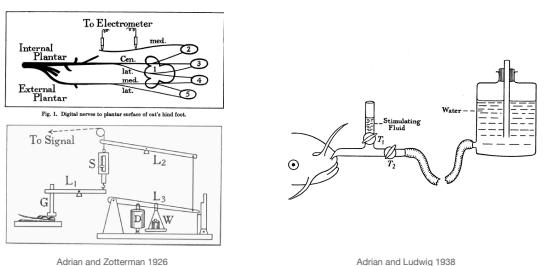
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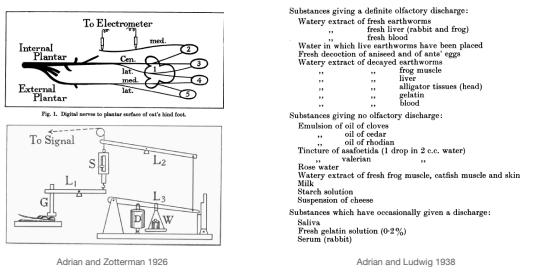
Pre-RF studies of sensory processing

Somatosensory Olfactory



Pre-RF studies of sensory processing

Somatosensory Olfactory

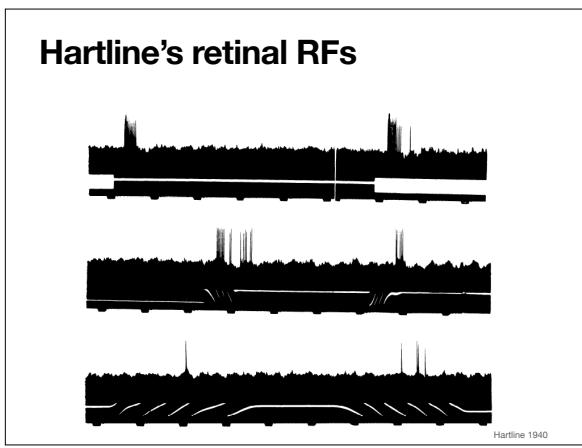
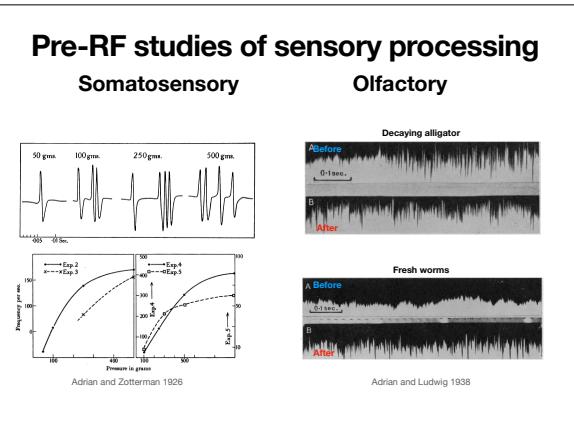


At each site that was stimulated, the minimal electrical stimulation strength required to elicit a reflex was noted. Sherrington presents this as a table, but I have converted this to a map on the surface of the dog. Deeper blues correspond to lower intensities required to elicit the reflex, i.e. increased sensitivity. Sherrington notes in his paper that the farther you get from the most sensitive point, the higher the threshold tends to be. Thus, not all parts of the skin are equally sensitive.

Following Sherrington's work the use of the term receptive field, and the method of systematically sampling a space of potential stimuli, was not readily adopted. Instead, sensory physiologists presented a variety of stimuli, without too much concern for their relation to one another. However, there was an emphasis in delivering stimuli consistently and precisely.

The two figures shown in this slide are stimulus delivery apparatuses designed by E.D. Adrian, a student of Sherrington and founder of in vivo neurophysiology.

As can be seen in Table 1 for his olfactory experiment, there was a wide variety of stimuli that were presented. Many of them are complicated substances, such as decaying earthworms, which were easy to fabricate but in retrospect yield neural responses that are difficult to interpret. This is because it is unclear exactly which aspect of the decaying earthworm causes a neural response.



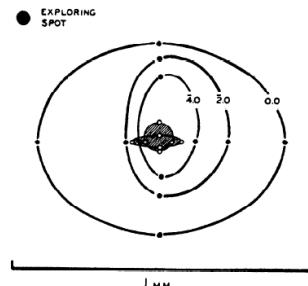
Adrian observed that as you increase the intensity of the stimulus the neural response tends to increase. Then, as you deliver a wider variety of stimuli, such as the olfactory, you can see that responses are elicited. However, it is unclear how these responses relate to one another. It is one thing to show that two stimuli can drive a neural response, but ultimately if we want to understand 'coding' in the nervous system, we need to understand how the neural representations of stimuli relate to each other.

The concept of the receptive field for sensory physiology was introduced by Hartline in the 1930s who was studying neural responses in the horseshoe crab and frog retina. In the case of the frog retina, he would move a spot of light (or shadow) across the retina. Its nerve was dissected/split to isolate a single axon (putatively), which was attached to an electrode and recorded.

The top trace shows the response to constant illumination. This cell is responsive to the onset and offset of the light stimulus.

The bottom two are responses to moving illumination, with faster movement eliciting a greater response.

Hartline's retinal RFs



Hartline 1940

So far his experiment has been similar to Adrian's, but what set Hartline's apart was that he systematically studied the response of the retinal ganglion cell to changes in the location of the light spot. What he found was that a single ganglion was sensitive to a relatively large area, much greater than the cell body. At the center of this area the response was strongest, and decayed as one moved towards the edges. This is analogous to the receptive field identified by Sherrington, hence why Hartline adopted the term.

When creating an RF, a stimulus space is defined. The space will have a set of dimensions. In this case there are two dimensions, the horizontal and vertical position of the light spot. Each dimension will also have a range of values it can take on. Consequently, almost always we define RFs with dimensions that can be numerically parameterized.

In this graph the solid spots indicate regions where the light elicited persistent firing.

Requirements for defining an RF

- **To construct:**
 - An input, physical modality
 - An output, neuronal signal
 - A way to define similarity between inputs or map them
- **To interpret:**
 - Mapping between input and output must be 'systematic'
- **To build upon:**
 - Relationship to perception
 - Combinatorial/hierarchical/multiplexed

From this example, we get a clear sense of how RFs are constructed and interpreted.

In addition, once an RF is identified, we can examine additional questions such as how its properties relate to the organisms perceptual abilities, and how receptive fields can be combined to create more complex representations.

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- General principles of RF

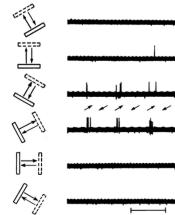
From here on out, we will survey some of the most commonly studied RFs.

Visual RFs

Early work, Hubel and Wiesel

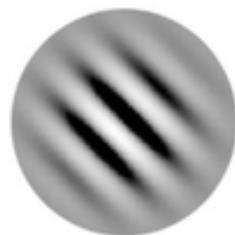
RECEPTIVE FIELDS OF SINGLE NEURONES IN
THE CAT'S STRIATE CORTEX

BY D. H. HUBEL* AND T. N. WIESEL*



It was a chance observation by Hubel and Wiesel (accidentally knocking a projector), that lead them to identify the space of stimuli that optimally drive neuronal responses in V1. They found that a bar of light moved across a specific area of the visual field would elicit spiking when it occurred at a particular angle. The further it rotated away from that angle, the less of a response was elicited.

Standardization of stimuli: Oriented gabors

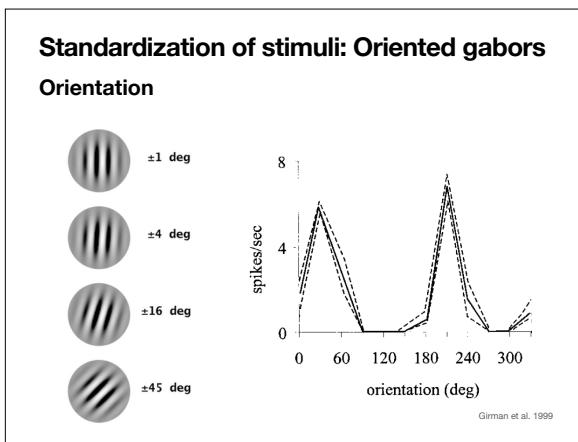


While bars of a light can be easily generated and their properties modified, modern visual physiologists use 2D gabor shapes that can be loosely thought of as a series of bars. The neural responses for many of the properties of gabor stimuli has been thoroughly studied, so we will focus on them.

Gabors have an additional advantage: when an encoding model is optimized to use sparse representations that preserves the information content of naturalistic images then it settles on gabor filters (Olshausen

and Field 1996).

Gabors come out of the drifting grating stimuli, which were first used in Enroth-Cugell and Robson 1966.

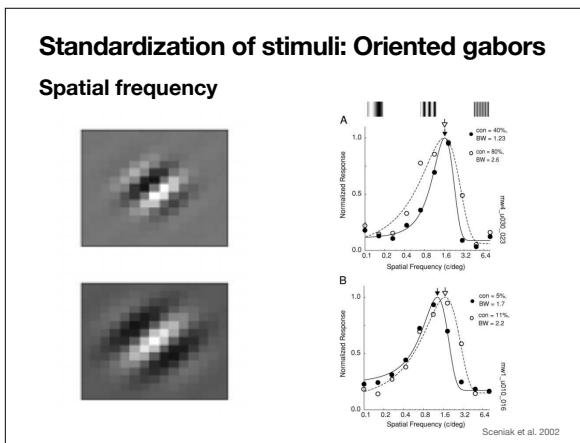
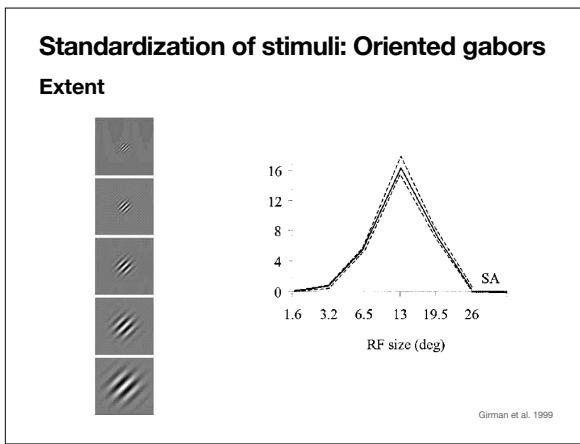
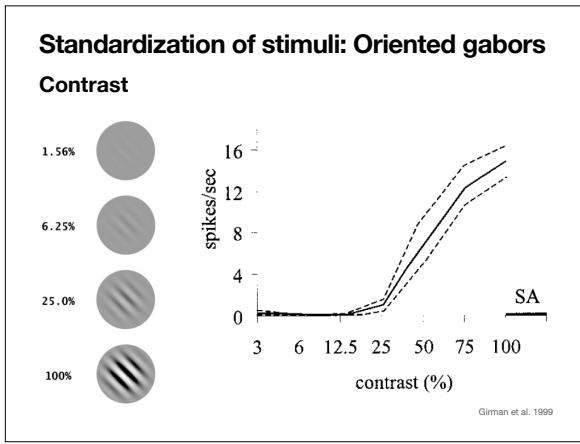


Orientation tuning is one of the most well studied features of neural coding for gabors. In general, neurons respond preferentially to a specific orientation, with the response fading out when you get more than >30 degrees away from the preferred orientation.

In this example, the orientation is varied from 0 to 360 degrees, and the evoked firing rate of a neuron at each orientation is recorded. A note about terminology: when the neural response is plotted against only one stimulus dimension it is typically referred to as a ‘tuning curve.’

Throughout this lecture I will use these terms interchangeably. You should note that there are two peaks in this tuning curve, one around 30 degrees and the other at 210. This is because as the gabor is rotated it repeats itself after 180 degrees. Since, $180 + 30$ is 210, the response will repeat as well. It is common to only plot orientation tuning curves over a 180 degree range to avoid this.

If the bars of the gabor are moving, however, then rotating it 180 degrees will change the direction of motion, which some cells are sensitive to.

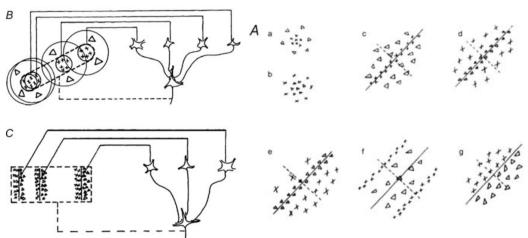


By varying the degree to which the black and white stripes of the gabor deviate from a gray background, the contrast can be varied. Neurons in V1 typically respond with increasing vigor as the contrast is raised.

Neurons also exhibit preferentially responses to gabors of particular sizes. As they increase in size, a neuron will increase its firing rate. But, if the size goes beyond a particular limit, it will drive down the response. This is due to several factors, but a major contributor is the presence of surround inhibition. As more neurons adjacent to the one you are recording from are recruited, they will activate inhibitory interneurons that silence the network.

Spatial frequency can also be varied by changing the distance between the light and dark regions of the gabors. Neurons are also sensitive to this parameter. The tuning curves seen here were from monkeys, the spatial frequency range is quite large relative to those from rodents, which tend to be less than 0.3 c/deg. This may be relevant to the fact that rodents generally have lower spatial acuity than primates.

Construction of more complicated RFs



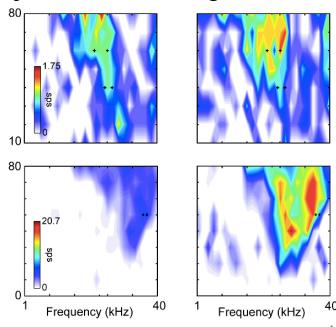
A benefit of orientation tuning is that it fits mid-way within a hierarchy of representations. The spot responses of retinal ganglion cells/thalamic neurons can be arranged in a line to produce such an RF, and the orientation tuning of V1 neurons can be combined to produce larger and more complex ‘edge’ detectors that are found in the next level of processing in the visual system.

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Auditory RFs

Frequency and volume tuning



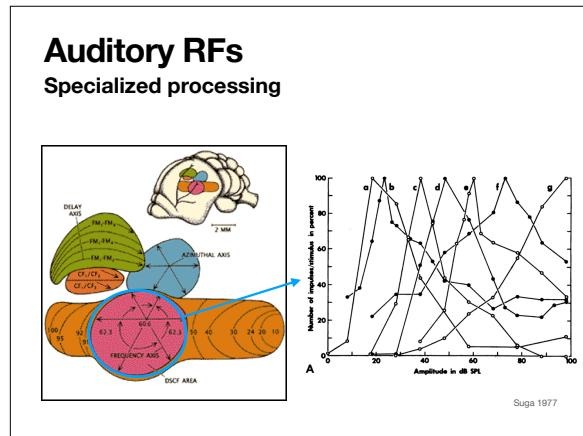
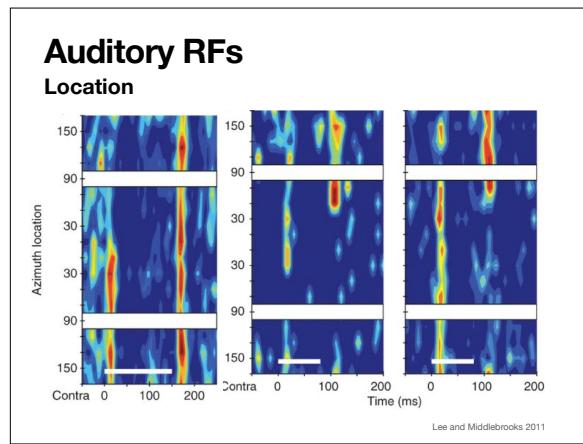
Compared with the visual system, much less is known about tuning in the auditory system. We do know that neurons in auditory cortex respond to sounds, and individual neurons have a preferred range of frequencies that drive their activity. As you increase the volume of a specific frequency, a neuron will fire more. Combining the frequency and volume dimensions, auditory physiologists produce ‘frequency response areas’, which is just a name for a particular kind of RF.

To generate these RFs, researchers will play hundreds or thousands of tone ‘pips’, ~50 ms long tone pulses with a particular frequency and

volume.

As can be seen the attached figure, the RF has a 'V' shape, with the breadth of frequency tuning narrowing as the volume decreases.

Note that the frequency range goes up to 40 kHz in this rodent example, which exceeds the primate hearing range.



Besides frequency and amplitude tuning, neurons in auditory cortex are also sensitive to the location of sounds. While the coding for this parameter is still not well understood, systematically varying the position of the sound changes the neuron's response to it.

Here are three examples of location sensitive responses. The sound itself was unchanged, but the location it was delivered from varied around the subject (azimuth axis).

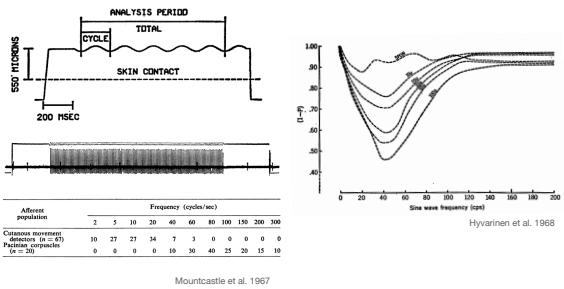
Some species exhibit highly specialized auditory tuning that befits their ethology. For instance, bats use echolocation to navigate and so their auditory cortex features several zones that are sensitive to the properties of reflected sounds. One such example is the doppler shift sensitive area (DSCF), which contains neurons whose preferred frequency is limited to a narrow range centered on the bat's echolocation vocalization frequency, and who exhibit sensitivity to specific volumes. This is in contrast to the general rule we discussed for auditory tuning a couple slides back, where neurons almost invariably increased their response as the volume

increased.

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Somatosensory RFs Early work, Mountcastle

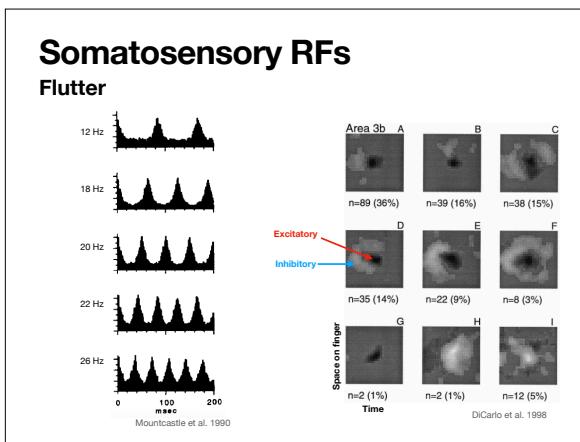


By the time Vernon Mountcastle conducted his pioneering work, it had already been established that somatosensory cortex had a ‘somatotopic’ organization. That is, the body surface was systematically represented across the cortical surface, with the feet at the dorsal/central most portion of the cortex, and the face at the ventral/lateral most area. Thus, neurons in those areas, in all likelihood, had a receptive field that encompassed a specific portion of the body. However, the nature of the stimulus that drove their response was unclear.

Mountcastle found that peripheral receptors in the skin were sensitive to

vibrations of the skin surface (also referred to as ‘flutter’), ranging up to 300 Hz. Different skin receptors have different sensitivities to flutter frequency (table bottom left).

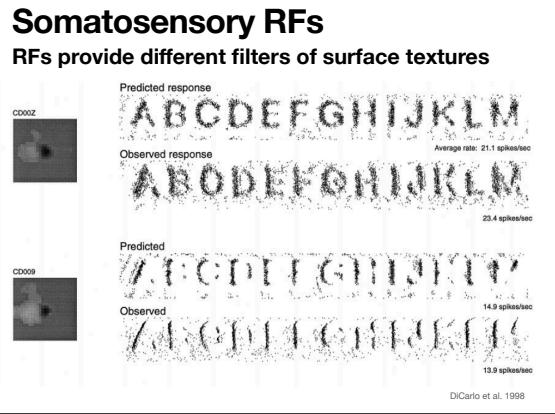
He then investigated the response of neurons in primary somatosensory cortex (S1) to flutter stimuli, and found that on average neurons responded most strongly the flutters around 40 Hz, and their response increased with amplitude of the flutter. But they did not show the same range of preferences for flutter frequency.



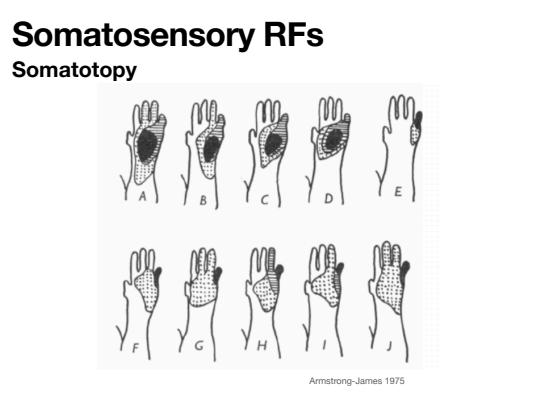
The lack of variety in the optimal flutter frequency seems to indicate that while flutter frequency is represented in the periphery, neurons in S1 will spike during each pulse of the flutter at the rate of the flutter (up to a limit). Thus, since flutter frequency is not differentially represented across neurons, it is unlikely we would consider it to be represented by a proper RF.

One of the implicit assumptions of RF identification is that the parameters of the RF vary across neurons. In doing so, the corresponding stimulus feature is represented by the neurons at the population level (sometimes referred to as a spatial code).

Instead, in S1 there is a temporal code for flutter (chart on the left), but this is not commonly subjected to RF analysis. However, neurons are sensitive to skin deflections, and exhibit a central patch that can be either excitatory or inhibitory, with a surround that is almost always inhibitory.



Changes in the shape of the excitatory and inhibitory regions, along with their strength, create different kinds of filters for surface texture. In this figure, a neuron's RF was determined and its response to a series of small letters run against the finger tip was measured. The observed response can be compared with the one predicted from the RF. For the top neuron, it had a large excitation at the time of deflection followed by relatively weak inhibition. This produces a response that mimics the shape of the letters. On the other hand, the bottom neuron had a weak central excitation followed by a strong inhibition, this made the cell sensitive to the start of each letter, essential acting as a detector for edge onsets.



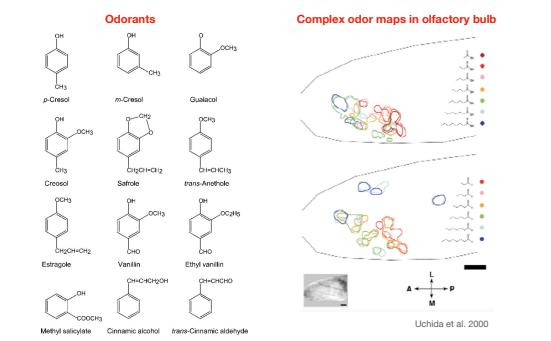
Besides surface texture, neurons in S1 show RFs for specific areas of the body. Thus, each neuron can be thought of as encoding the texture on a particular patch of skin.

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Olfactory RFs

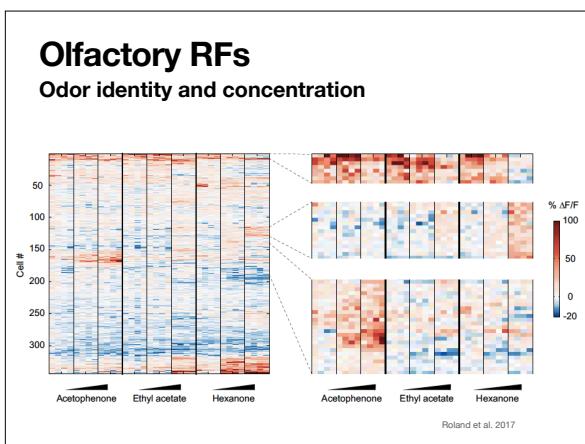
Can a 'field' be defined?



The olfactory system has largely defied simple explanation with regard to RFs. Part of the problem is that it is unclear how to order odorants with respect to one another (left graph). Since one of the first steps in constructing an RF is to define a stimulus space, it seems that odors will present a distinct challenge. One way around this is to focus on a specific class of chemical compounds, where we can make a single change to their structure (right graph). In this example, a single methyl group is appended each time, creating a longer and longer carbon chain. The topography of each compound's activity on the olfactory bulb is noted. Why measure this? In the previous sensory systems the we saw that the organization of receptors at the periphery (retinotopy, tonotopy, and somatotopy), influenced the coding in the cortex. The corresponding area to observe this for olfaction would be the olfactory bulb. While the related compounds tend to activate similar areas of the olfactory bulb, the precise pattern varies even among these highly similar compounds. Thus, even at the level of the periphery the olfactory system is already presenting challenges.

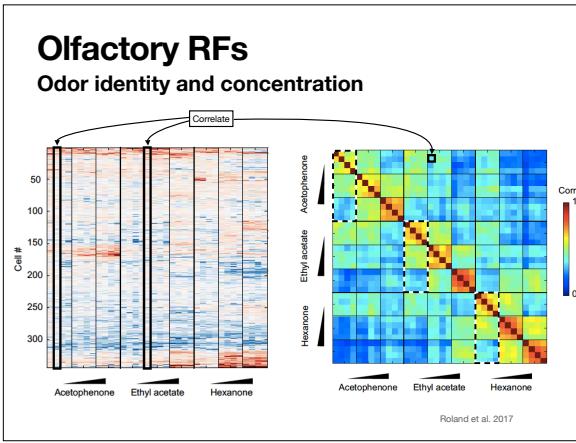
Piriform cortex is the primary olfactory input into cortex, so we will focus

our discussion on that area.



Besides the identity of the chemical, we also care about its concentration. We might analogize this to the contrast of an oriented gabor, or the loudness of a tone pip. In both of those cases, increasing their value tends to enhance the response they show at lower intensities. Perhaps this is the case for olfaction?

To determine this, one can present different odorants, each at different concentrations, and analyze how neurons in piriform cortex respond to them. For the attached graph, each odorant is shown below, and they are each presented at 3 different concentrations (each separated by the black vertical lines). Each row corresponds to a different neuron.



By measuring the correlation in the response across neurons between odors, we can see what aspects of the odor are encoded similarly at the population level. Each black square corresponds to a different combination of odorant/concentration, with 4 presentations of each. Along the diagonal, the blocks' of red/yellow correspond to correlations between populations responses to the same odor/concentration. These have the strongest correlations, while those that are between the same odorant at different concentrations, which are the immediately off-diagonal blocks, are green/yellow (indicating moderate correlation). Finally, comparing between different odors, the way-off-diagonal blocks are green/blue, which have the lowest correlation.

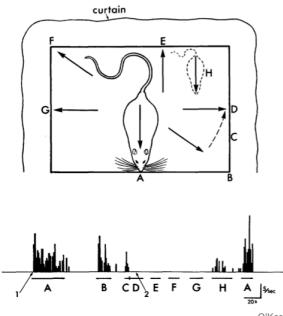
Thus, odors are coded uniquely at the population level in a way that is partly concentration invariant. And increasing the concentration of the odor makes the cortical representation more distinct. This is broadly in agreement with the RF properties we saw in the other three cortical areas, just without any apparent order along the odorant dimension.

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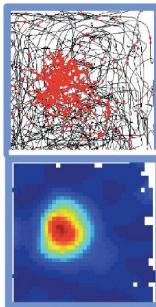
Hippocampal RFs

First evidence for place coding



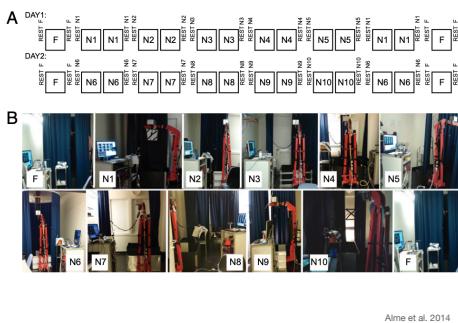
Hippocampal RFs

How to construct a place field



Hippocampal RFs

Place/context coding



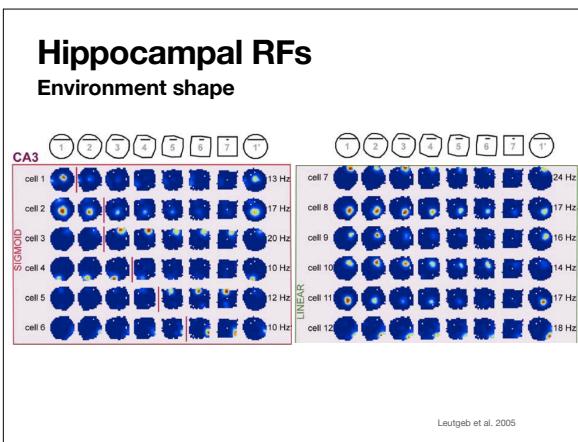
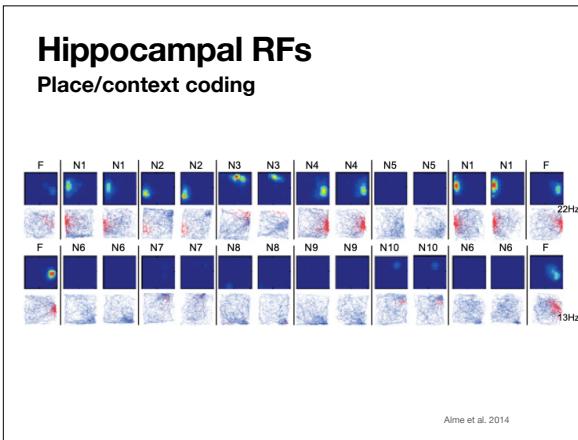
The first description of place cells did not feature a receptive field. But, it did show that the firing rate of a neuron in the hippocampus was systematically related to the location a rat was held in a room.

The top schematic shows the locations the rat was positioned in within in room. The bottom graph shows the spiking activity of a hippocampal neuron at each of those positions. The firing rate was strongest when the rat was held at and facing location A.

Virtually all place fields are constructed by allowing an animal to freely explore a space while recording its spiking activity. The space is then binned and the number of spikes fired at a particular binned location is counted and divided by how long the rat spent there.

The top graph shows the trajectory of the rat in black. Whenever a spike was emitted, a red circle is added to the line. The bottom graph is the firing rate across the binned space.

Over the last 20 years the Mosers and colleagues have thoroughly characterized the properties of place cells. For instance, they have explored how the place field that a rat forms for a box varies as a function of the room it is in. This slide illustrates their experimental design, with the same box used across 11 different rooms.



They found the place field shifts depending on the room the rat is in. Thus, the place RF is sensitive to the distal cues presented by the room. Similar to the problem faced by the olfactory system, it is difficult to parameterize the room context, given how many variations there are.

A more tractable approach is to systematically vary the shape of the box the rat is placed in. In the experiment illustrated above, the box was transformed from a circular to a square shape. As this transformation progressed, the place field could either fade out or in, while remaining in the same spot. Sometimes this happened abruptly (left graph), and could also occur gradually (right graph).

General principles

Necessary steps

- A stimulus space must be defined.
- Stimuli are generated by some means (oriented gabor, tone pips, etc) that span that space, and typically are artificial.
- Measure the neural response (e.g. count spikes).
- Identify characteristic shapes that typify the receptive field and quantify their properties (e.g. preferred orientation).

Assignment and next lecture

Assignment:

You will be assigned a paper with receptive fields. For each of the principles discussed in the previous slide, identify how they are applied in your paper.

Next lecture:

We will cover how receptive fields are calculated in greater detail and used to predict neural activity.