

β -catenin/Armadillo and TCF. *Drosophila* APC has a role in maintaining adherens junctions, and also helps to tether mitotic spindles to the cortex and to orient them in the epithelial plane. In mammalian cells, APC has been implicated in cell migration. APC also helps safeguard the fidelity of chromosome segregation in mitotic cells. Loss of APC's various functions at the cell periphery may contribute to tumour progression. The multitude of these functions could explain why APC is such a potent tumour suppressor.

Is there anything we don't know? It is unclear whether APC is a genuinely multi-functional protein, or whether there is one basic molecular activity that underlies all its apparently disparate functions.

How can I find out more:

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Primer

Receptive fields

Peter Lennie

Sensory organs are filters: they use some of the information that impinges on them, and block the rest. The most aggressive filtering occurs very early. The optical components of the eye and the photoreceptors of the retina, for example, together ensure that the human visual system normally responds only to light of wavelengths from 400–700nm. Equivalent constraints confine the kinds of signals that are handled by other sensory systems. Even though much raw information is discarded by the initial transduction stage that converts visual, auditory or other sensory signals into activity in the nervous system, a tremendous amount is admitted — far more than the brain can deal with.

Consider what happens in the visual system. There are about 6 million cone photoreceptors in the human eye, each of which provides a point sample of the retinal image. But the optic nerve, through which all signals are conveyed from the eye to the brain, contains only 1.25 million nerve fibers, each of which can carry less information than a single cone. This loss of information in the eye is not

necessarily troublesome: the retinal image, like most sensory signals, is redundant, and one part of the image can to some extent be predicted from the structure of nearby parts, but for adequate prediction the right information has to be preserved.

The visual system, like other sensory systems, therefore needs selective filters designed to transmit the important structure in natural signals. Filters are embodied in individual neurons in the retina and higher stages of the visual pathway, and have characteristic properties that determine the spatial and temporal attributes of the signals they transmit. The natural way to represent the spatial attributes of the neuronal filter is through a map of the region of retina from which the neuron picks up signals. This map is called the neuron's 'receptive field'.

Figure 1 shows two representations of the receptive field of a mammalian retinal ganglion cell (the axons of ganglion cells form the optic nerve and convey the results of retinal processing to the brain). On the left, the receptive field is represented as a three-dimensional profile, with excursions above the plane denoting regions of retina where light stimulation excites the cell, and excursions below the plane denoting regions where light inhibits the cell. On the right, the receptive field is represented as a plan view overlaid on the

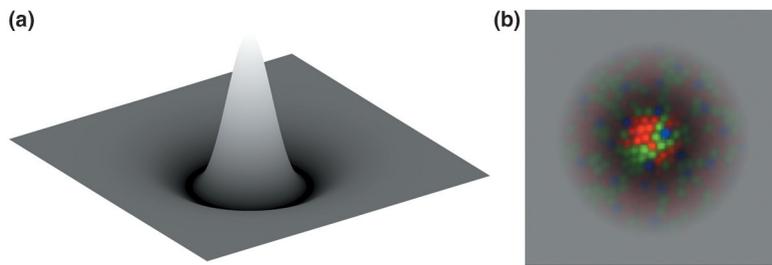


Figure 1. The receptive field of a mammalian retinal ganglion cell. (A) Three-dimensional representation of the distribution of sensitivity. The receptive field is composed of two distinct mechanisms, center and surround, each of which weights signals from photoreceptors by a two-dimensional Gaussian profile. Signals in center and surround are of opposite polarity, and are summed by the ganglion cell. The center is smaller than the surround, but the integrated sensitivities of the mechanisms are nearly the same, so the cell responds poorly to uniform illumination that covers the receptive field. (B) Plan view of the receptive field, with shading indicating the weights with which it draws on signals from underlying cone photoreceptors.

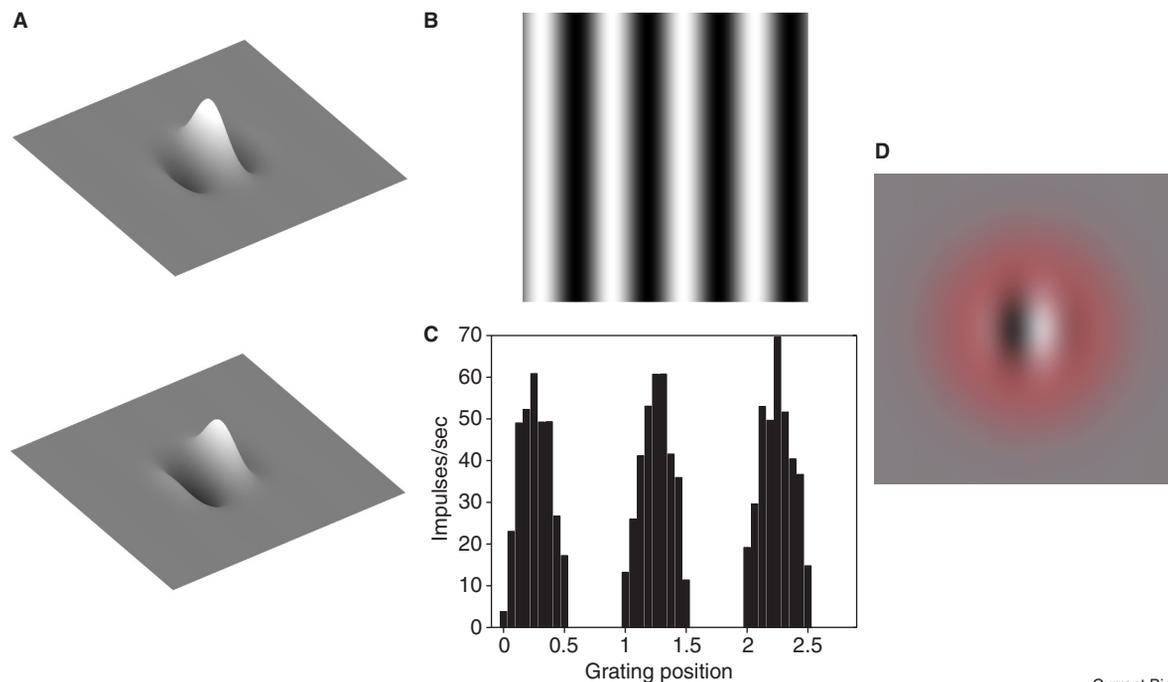


Figure 2. The receptive field of a 'simple' cell.

(A) The receptive field profile can be conceived as a sinusoid weighted by a two-dimensional Gaussian envelope. Different relative phases give rise to receptive fields with even (upper) or odd (lower) symmetry. (B) Sinusoidal grating patterns are often used to characterize the spatial properties of the receptive field. (C) The simple cell's response to a grating pattern moving across the receptive field is a truncated and distorted sinusoid. (D) The simple cell's response is regulated by gain-controlling signals accumulated from a region (here identified by red shading) that contains and extends beyond the receptive field.

mosaic of cone photoreceptors that pick up the image, with the lightness/darkness indicating the sign and strength of the signal received from each cone.

This kind of receptive field — often called a 'center-surround' receptive field — confers interesting properties on its cell. Because the cell generally sums the signals gathered from all points in the receptive field, it will respond poorly to uniform illumination of the whole receptive field — excitatory signals are broadly balanced by inhibitory ones. More generally, the structure of the receptive field enables the cell to block signals that are common to the center and surround, in the manner of a differential amplifier. As a result the neuron transmits information about local spatial contrast in the image.

For any visual system capable of rich analysis of images, it is important not to discard information too early. Neurons with center-surround receptive fields generally behave as simple

linear filters which impose a modest transformation on the visual image. They discard the least important information, and condition the image for economical transmission to mechanisms that undertake fuller analysis of it. They are the commonest kind in the retinas of higher mammals.

Other sorts of neurons have more elaborate receptive fields. Figure 2A shows examples of a relatively simple extension of the receptive field in Figure 1. The distribution of sensitivity in excitatory and inhibitory regions is different, and confers a greater spatial selectivity on the neuron, notably making it tuned for oriented contrast in the image. Otherwise, the neuron accumulates signals linearly, and can still be thought of as a simple image filter, constructed straightforwardly through combining inputs from appropriately arranged center-surround receptive fields. The structure of a receptive field can be explored with methods for

analyzing linear systems; sinusoidal contrast patterns are therefore often used (Figure 2B). Neurons with this kind of receptive field — called 'simple' cells — are common in mammalian primary visual cortex.

Although the cells illustrated in Figure 2 accumulate contrast signals linearly, their responses — expressed as the rates at which they discharge spikes — do not accurately track variations in this signal, principally because simple cells have little or no resting discharge, and cannot respond at rates below 0. Their responses to patterns that move across the receptive field are consequently halfwave rectified (Figure 2C).

Simple cell receptive fields are spatially localized, oriented, spatial-frequency-selective filters. For any one small region of retina, a set of simple cells tuned to a range of orientations and spatial frequencies samples the image. A recent insight about them is that the design of their receptive fields is well-suited to

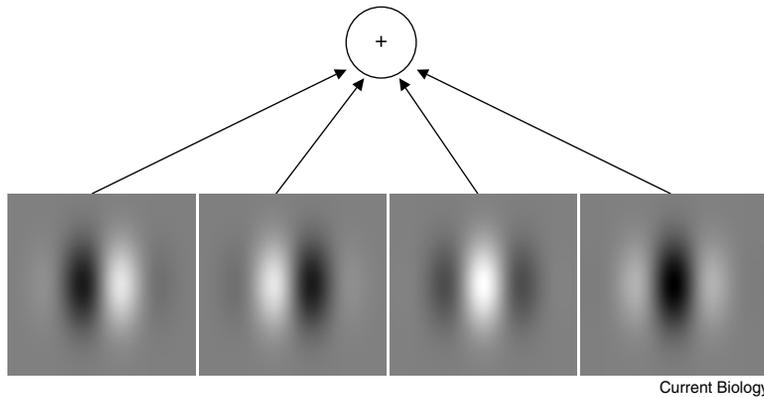


Figure 3. The receptive field of a 'complex' cell. Complex cells seem to be driven by signals from at least four simple cells, the receptive fields of which lie in the same place but prefer stimuli in different spatial phases. At least one of the simple cells will be active no matter what the spatial phase of the stimulus on the complex cell's receptive field, and because the driving signal is half-wave rectified, the complex cell will always respond.

represent the structure of natural images efficiently. That is, given the task of representing the spatial properties of natural images, and the requirement that it be accomplished by minimizing the statistical dependence among activity in neurons that respond to the image, a good choice is to use filters that have receptive fields of the kind found in simple cells.

Although such a set of linear filters helps represent the image efficiently, the complex structure of most natural scenes ensures that activity in different filters will still be substantially correlated. Real simple cells seem to possess additional, nonlinear mechanisms that can act to reduce the statistical dependence among their responses to natural images.

A simple cell has what is essentially a divisive gain control, which automatically regulates the rate at which spikes are generated, according to the contrast signal accumulated from its receptive field. This gain control is driven, not just by the individual simple cell, but by signals gathered from a pool of other cells that have receptive fields nearby. The greater the activity in this pool of neurons, the more the simple cell's gain is reduced. As the pool contains neurons that are tuned to a range of spatial frequencies and orientations and positions, the

aggregate gain controlling signal tends to be more broadly tuned than the signal that arises in the receptive field, and is accumulated from a larger region of visual field.

The gain-controlling machinery does not excite the cell directly, but as its signal is gathered from an area larger than the receptive field, part of it can be explored in the surrounding region. This 'silent surround' has been known for a long time, but only recently has it become clear how it works, and that it might be important for the efficient representation of images. The surround and the receptive field proper tend to prefer the same visual stimuli, so the surround most reduces the gain of the response when the cell's preferred stimulus covers both it and the receptive field. The structure of natural scenes is such that adjacent regions of the image are generally much alike, so the surround will help reduce the redundancy in the image representation provided by simple cells.

The image transformations undertaken by neurons up to the level of the simple cell can be conceived as providing a compressed description: one could reconstruct the visual image (albeit without full fidelity) from the signals available in simple cells. What succeeds this? We might conceive of additional layers of

transformation that remove progressively more complex forms of redundancy in the representation of natural images, ultimately giving rise to extremely efficient descriptions. These transformations might involve the construction of receptive fields that select for complex features in natural images. The notion that sensory neurons might be 'feature detectors' has a long history, rooted in the idea that some objects in the world are important and others are not, and that the job of sensory analysis is to distinguish the important from the unimportant.

Although converging lines of thought suggest the existence of receptive fields that analyze complex features, the kinds of features that are important to an organism, and help it to distinguish predator and prey or to identify a potential mate, need not be the kinds that allow efficient descriptions of images. We know too little about the higher-order structure of scenes, or about what is visually important to animals, to be able to stipulate features that receptive fields should be designed to detect. Instead, we explore the properties of receptive fields in real visual systems, and from these properties try to infer function.

The visual system does indeed possess neurons with highly-selective receptive fields — for example, cells that respond best to stimuli of a particular structure moving across their receptive fields in specified directions at particular speeds. In lower animals, sharply selective cells can be prominent even in the retina, but in higher mammals they are seldom seen at a lower level than the cortex, reflecting the general principle that the more complex the sensory analysis of which an animal is capable, the more likely it is to be deferred to cortex.

Some complexity is present even in primary visual cortex. Figure 3 shows the underlying structure of perhaps the commonest type of receptive field in the primary cortex, whose organization can only be inferred,

not mapped directly. It can be conceived as being assembled from the receptive fields of several simple cells with receptive fields in the same place. Each contributing simple cell prefers the image in a different position on its receptive field, so the neuron that accumulates rectified signals from the set of simple cells will have the spatial selectivity of a simple cell, but will be excited no matter what the position of the preferred stimulus within its receptive field. This kind of neuron is called a 'complex cell'.

Although only a small step away from a simple cell, the complex cell has distinctively different properties that highlight important general issues. First, it is not obvious what image features the complex cell is designed to detect. It responds to contrast power in the image, in certain orientations and within a certain band of spatial frequencies; its receptive field is not well suited to identifying edges, or the sorts of image structure we normally think of as a feature. It is better suited to conveying information about the general structure of surfaces, as coarse or fine-textured, or having characteristic material properties. The complex cell's sensitivity to contrast power also makes it potentially useful in encoding image movement in contexts — such as optic flow arising from self-motion — where it might not be important to know what in the image is moving. Similarly, the complex cell can be well-suited to encoding position in depth, providing a signal about where an object is without necessarily indicating what the object is. Second, in discovering particular kinds of structure in the image, complex cells irretrievably discard information about its other attributes. To the extent that these discarded attributes are important for the overall representation of the image, parallel machinery must exist to detect them. We know generally how this machinery is organized, though the details are enigmatic.

In the first visual cortical area, where simple cells and complex

cells arise, there are few signs of other major types of cell that might be selective for more specialized image features. Indeed, to the extent that other distinct kinds of cell can be identified at all in primary visual cortex, they seem to be organized for handling information about color, and have receptive fields that are less selective than those of simple cells. Detectors for more specialized image features must emerge in higher cortical areas to which primary cortex transmits information, and their receptive fields must be constructed from signals delivered by simple cells and complex cells.

The gross organization of visual cortical areas and relationships among them are well established, principally through anatomical work. Each holds a two-dimensional map of the retinal surface. The map is distorted, though preserves the topology. The multiple areas are organized hierarchically with generally more than one at each level, so as we ascend the hierarchy we might expect to encounter neurons with receptive fields of increasing specificity and complexity. It has been surprisingly difficult to evaluate this idea.

The physiologist who explores receptive fields in higher visual areas has little guidance about what to expect. As a result, a receptive field is generally characterized using one of two approaches: by delivering standard stimuli, such as sinusoidal gratings, which under the right conditions permit powerful inferences about the underlying receptive field structure; or by using a repertory of perhaps richly structured patterns, some of which might contain the feature(s) to which the receptive field is tuned. Both approaches suggest that neurons in higher areas have more exacting stimulus requirements than those in early cortex, but neither approach has yet revealed much about the essential differences among areas or the

principles used to analyze the image.

As we learn more about the statistical structure of the visual world, and about the aspects of it that are most important to different animals, we can expect more sharply guided physiological explorations to reveal the details of the successive stages of image analysis.

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