Introduction to Neural Coding

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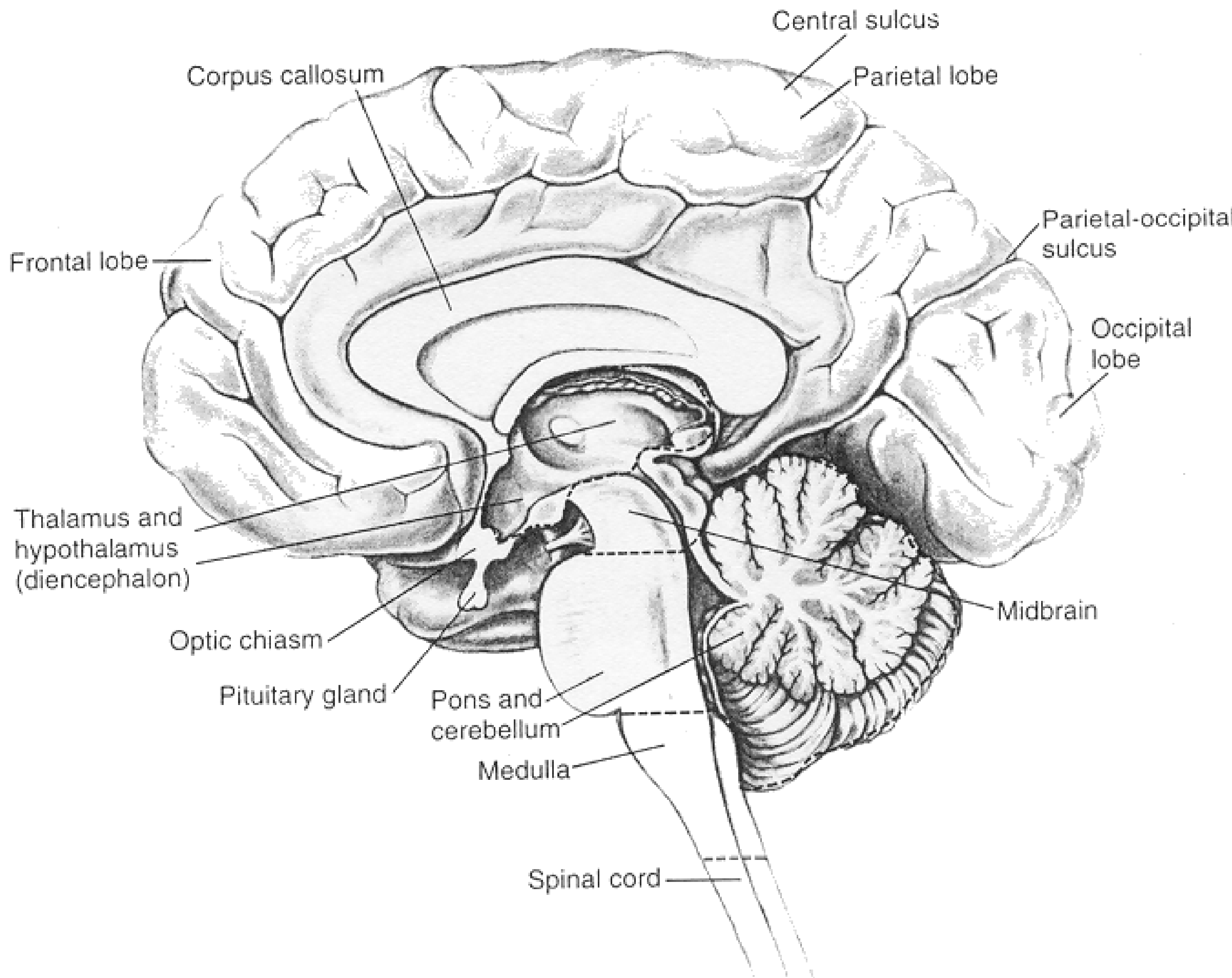
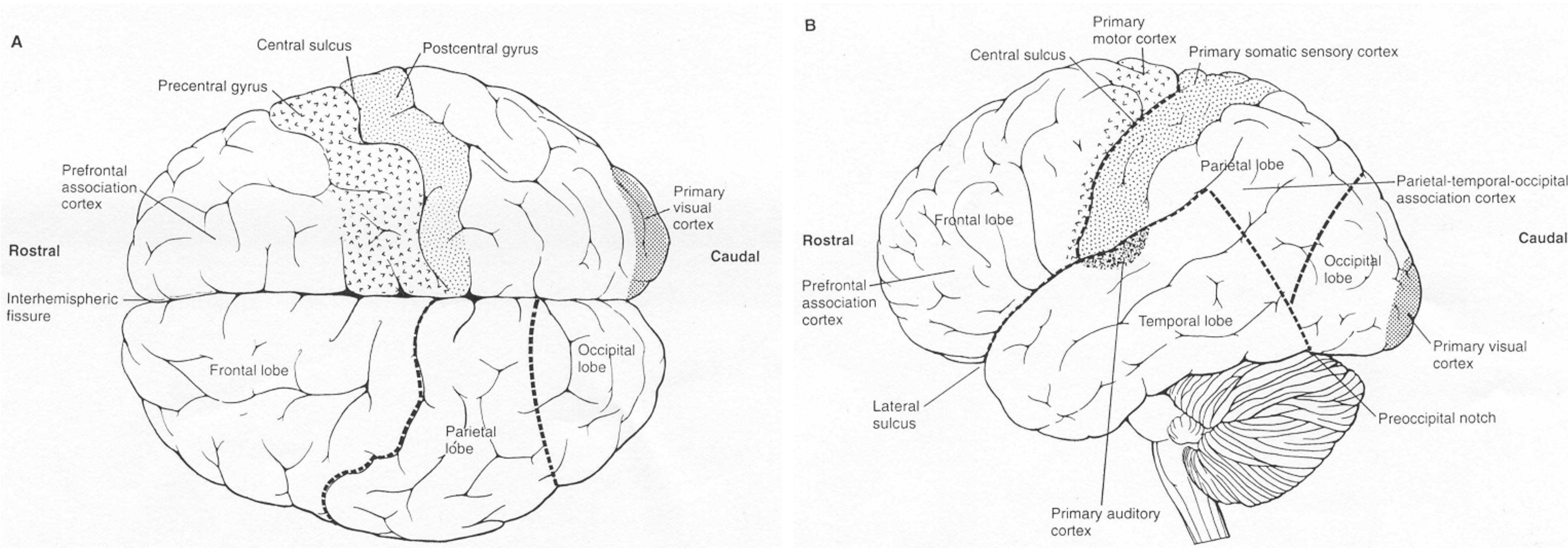
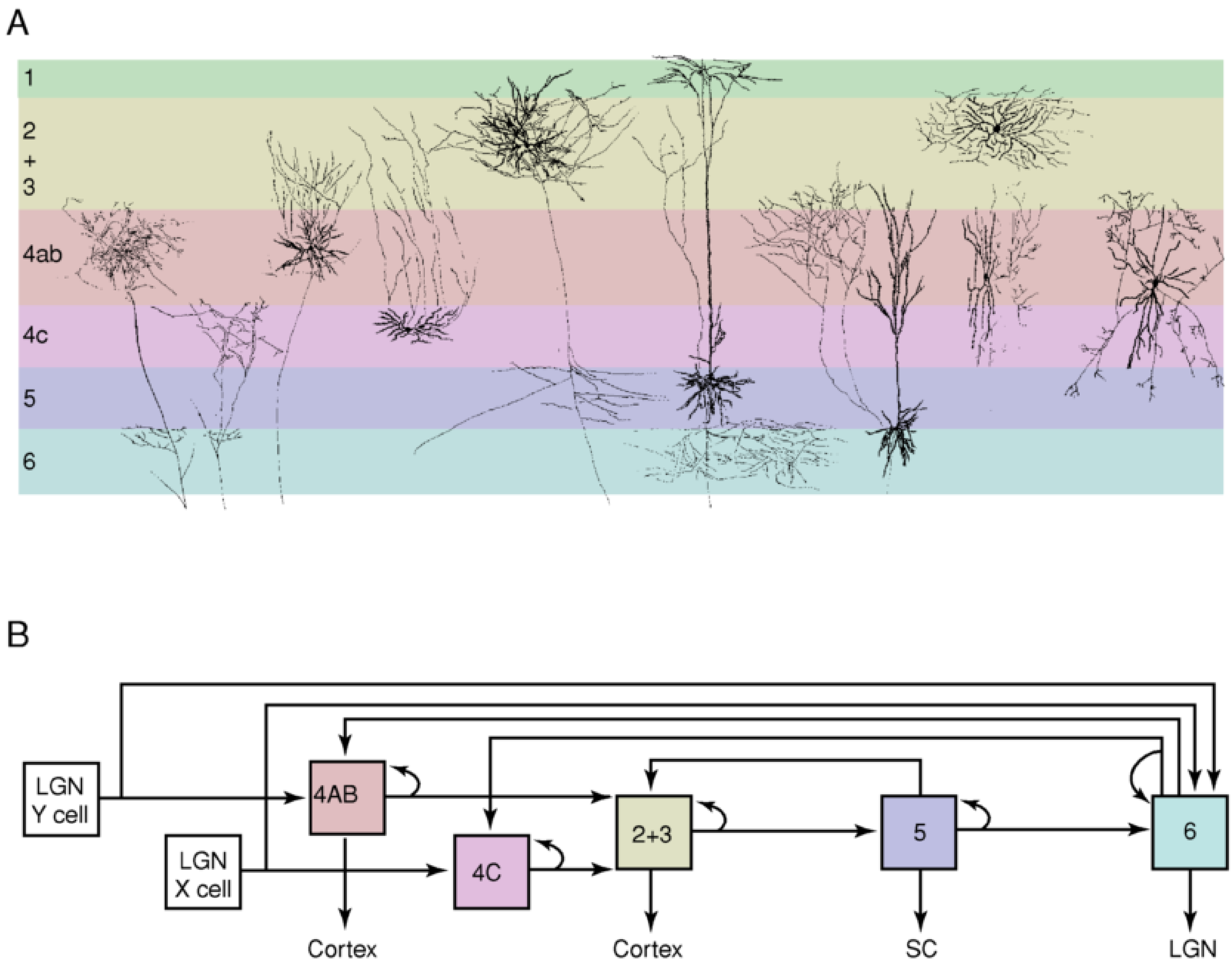
The CNS


Central sulcus
Corpus callosum
Parietal lobe
Parietal-occipital sulcus
Frontal lobe
Occipital lobe
Thalamus and hypothalamus (diencephalon)
Midbrain
Optic chiasm
Pituitary gland
Pons and cerebellum
Medulla
Spinal cord

Neocortex


A
Central sulcus
Postcentral gyrus
Precentral gyrus
Prefrontal association cortex
Primary visual cortex
Rostral
Caudal
Interhemispheric fissure
Frontal lobe
Occipital lobe
Parietal lobe
B
Primary motor cortex
Central sulcus
Primary somatic sensory cortex
Parietal lobe
Parietal-temporal-occipital association cortex
Frontal lobe
Rostral
Caudal
Occipital lobe
Prefrontal association cortex
Temporal lobe
Primary visual cortex
Lateral sulcus
Preoccipital notch
Primary auditory cortex

Cortical layers



Neural signals (in vivo)

Aggregate

- aggregate fields – EEG, MEG, LFP
- aggregate membrane voltage – die imaging
- metabolism – fMRI, PET, intrinsic imaging

Single neuron

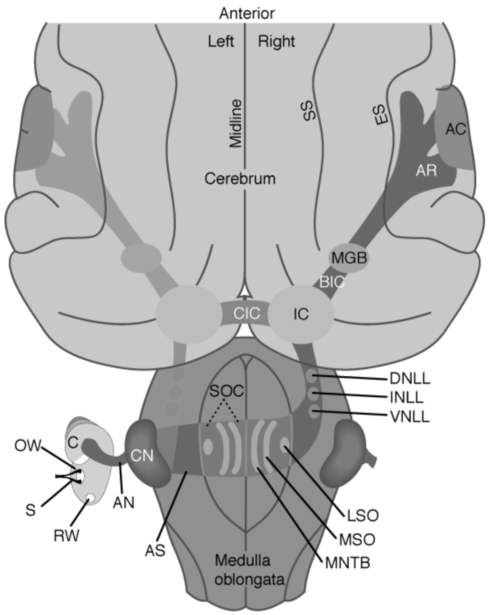
- extracellular – single neuron, spike sorting, cell attach
- intracellular – sharp electrode, whole cell

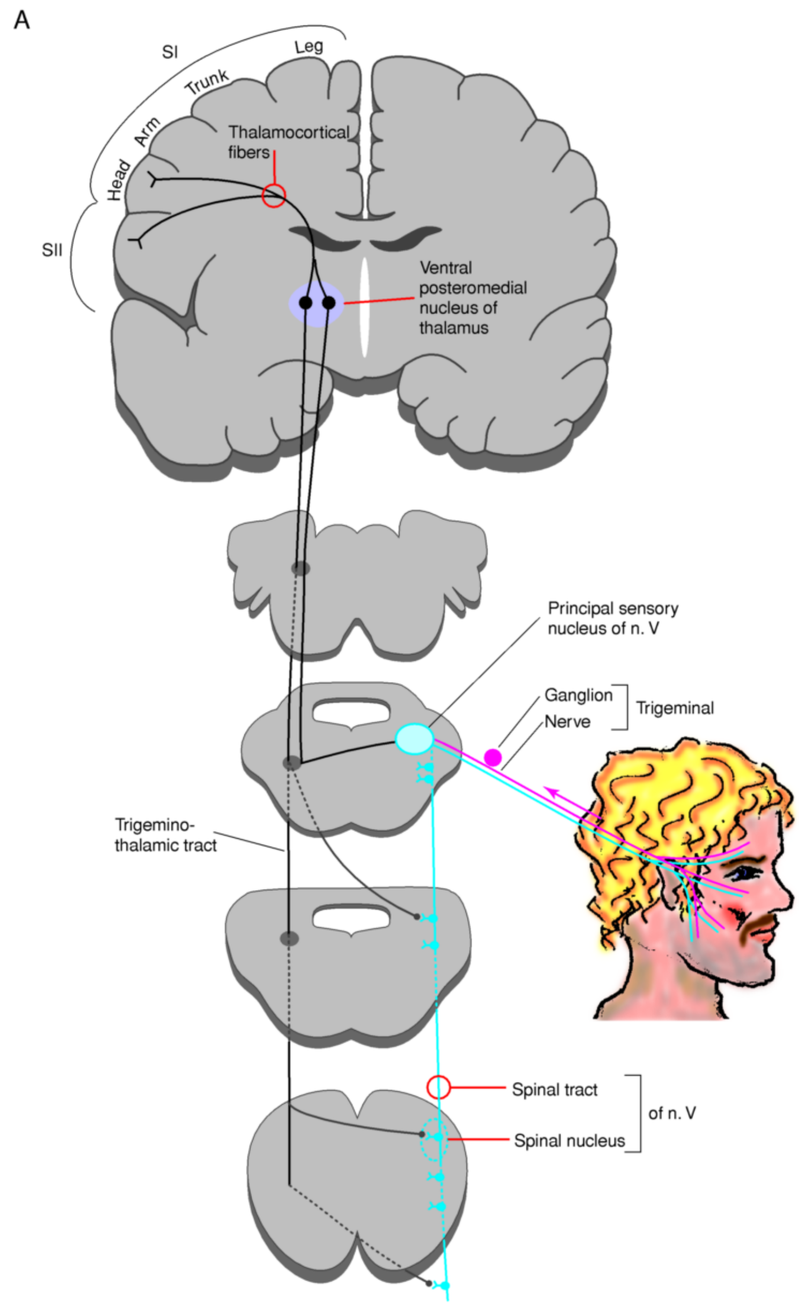
Senses

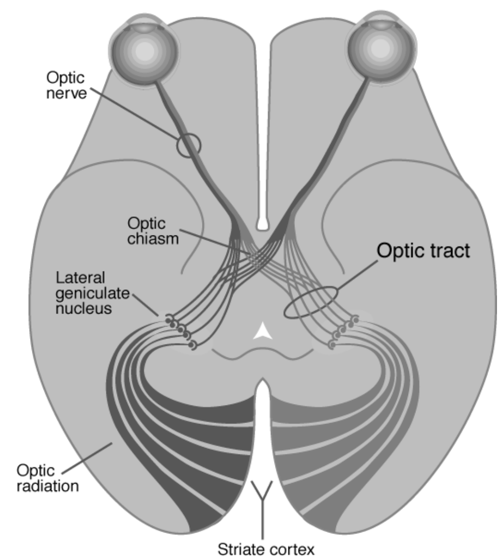
How many senses do you have?

- taste (gustation)
- smell (olfaction)
- hearing (audition)
- sight (vision)
- touch (somatosensation)
- pain (nociception)
- body configuration (proprioception)
- acceleration and balance (vestibular sense)

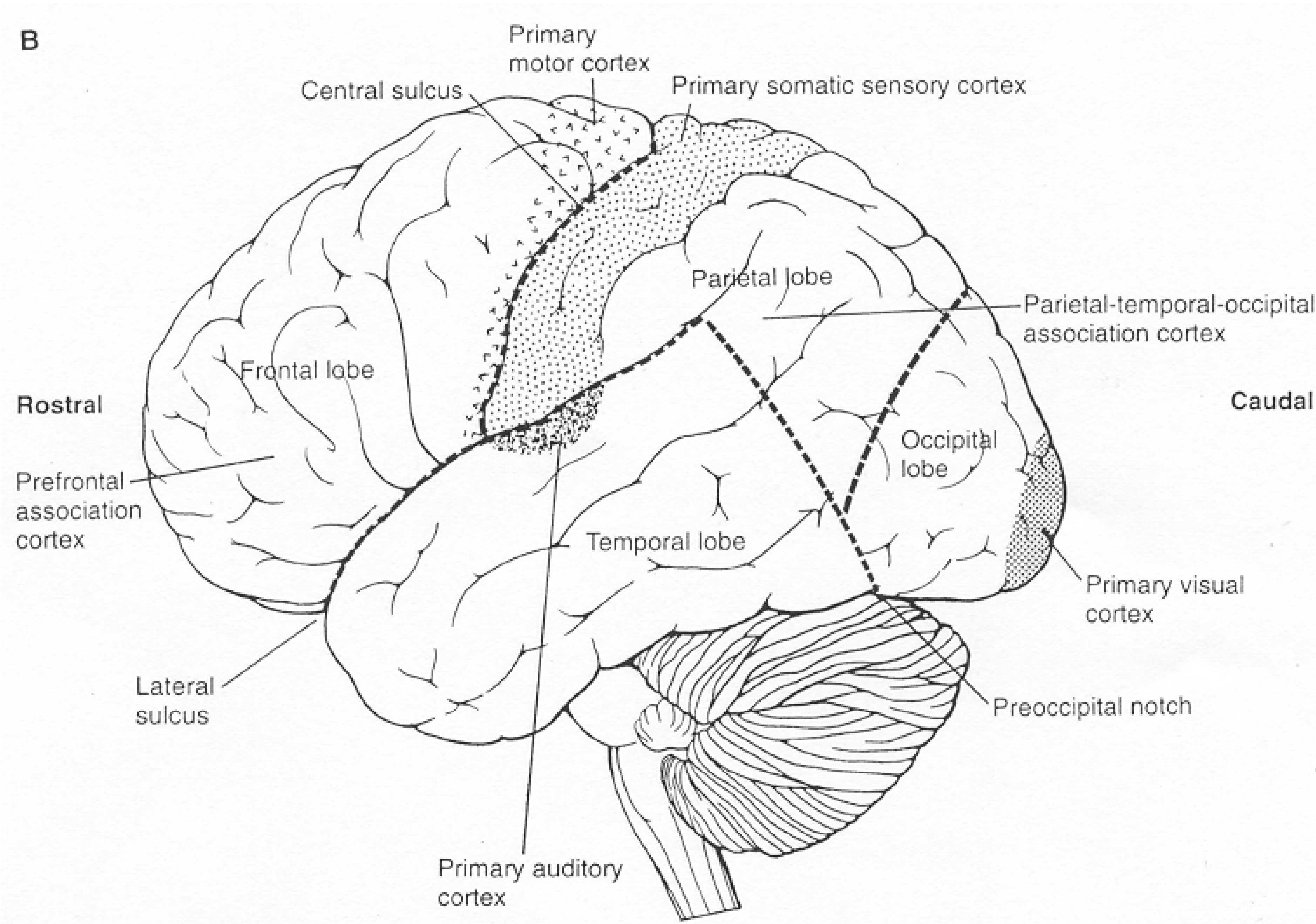
Neocortical senses







Sensory areas



Common features of neocortical senses

- common pathways: receptors – subctx nuclei – thalamus – primary ctx – higher ctx
- thalamic loops between cortical areas
- feedback
- parallel hierarchy
- alternate pathways – tectal, para-lemniscal

Common processing

- receptor discretisation – sampling
- receptive fields
- contrast sensitivity – Weber's law
- adaptation
  - neural vs. psychological
  - adaptation to higher features
  - mismatch negativity
  - statistical adaptation

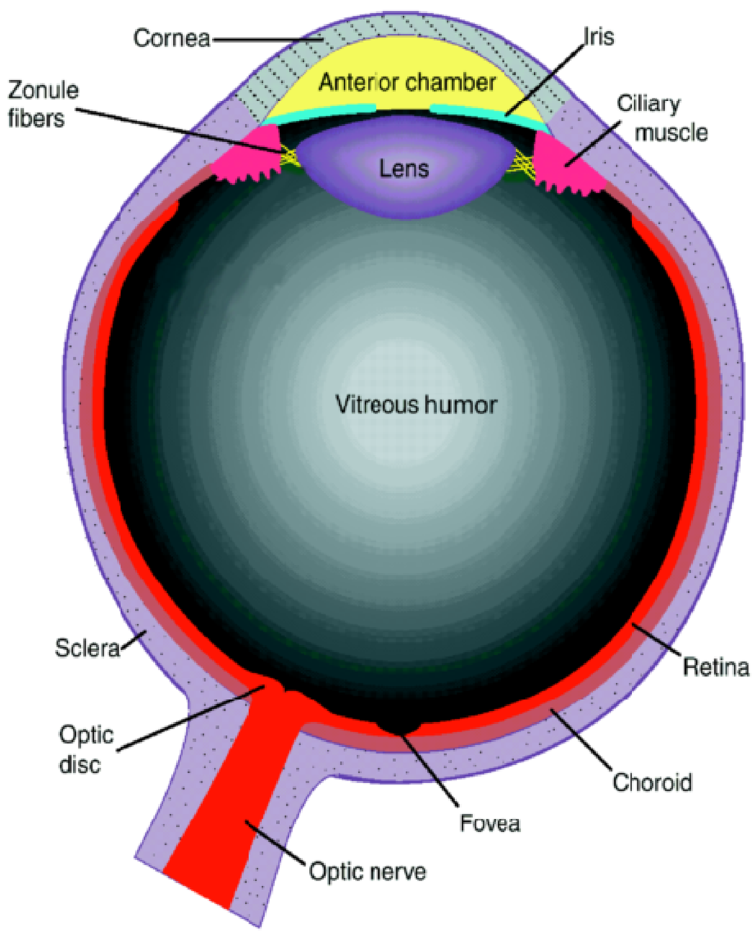
Quantifying responses

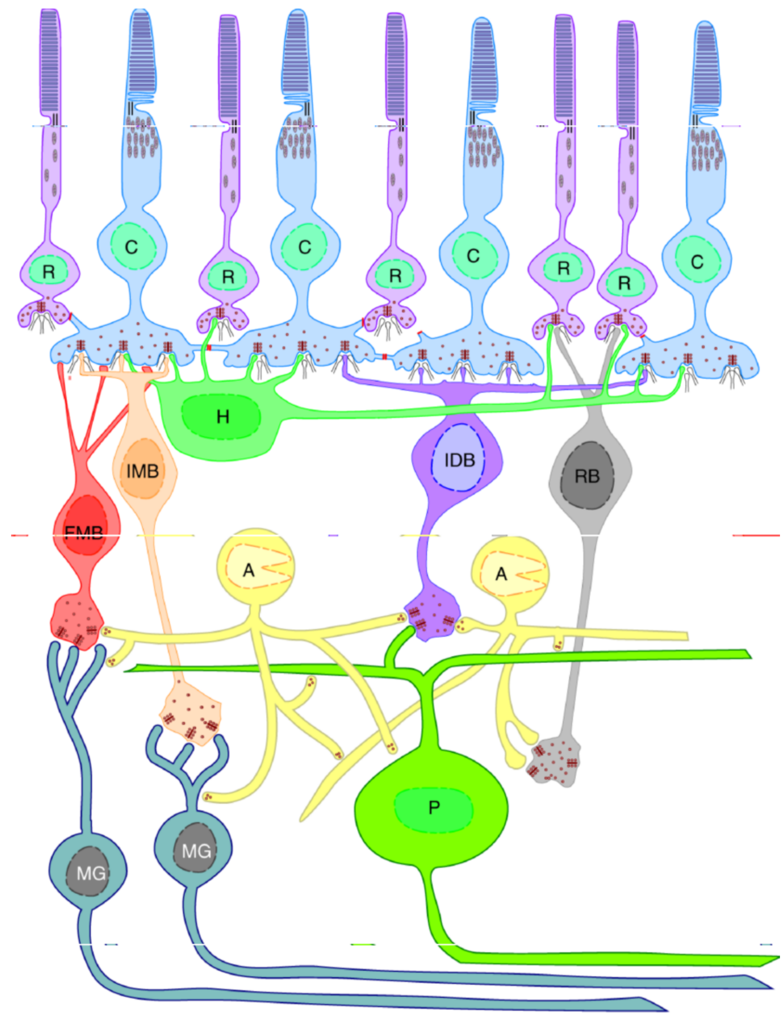
- receptive fieds
- motor fields
- stimulus-response functions
- sensory computation and encoded variables
- tuning curves

Optimality of coding

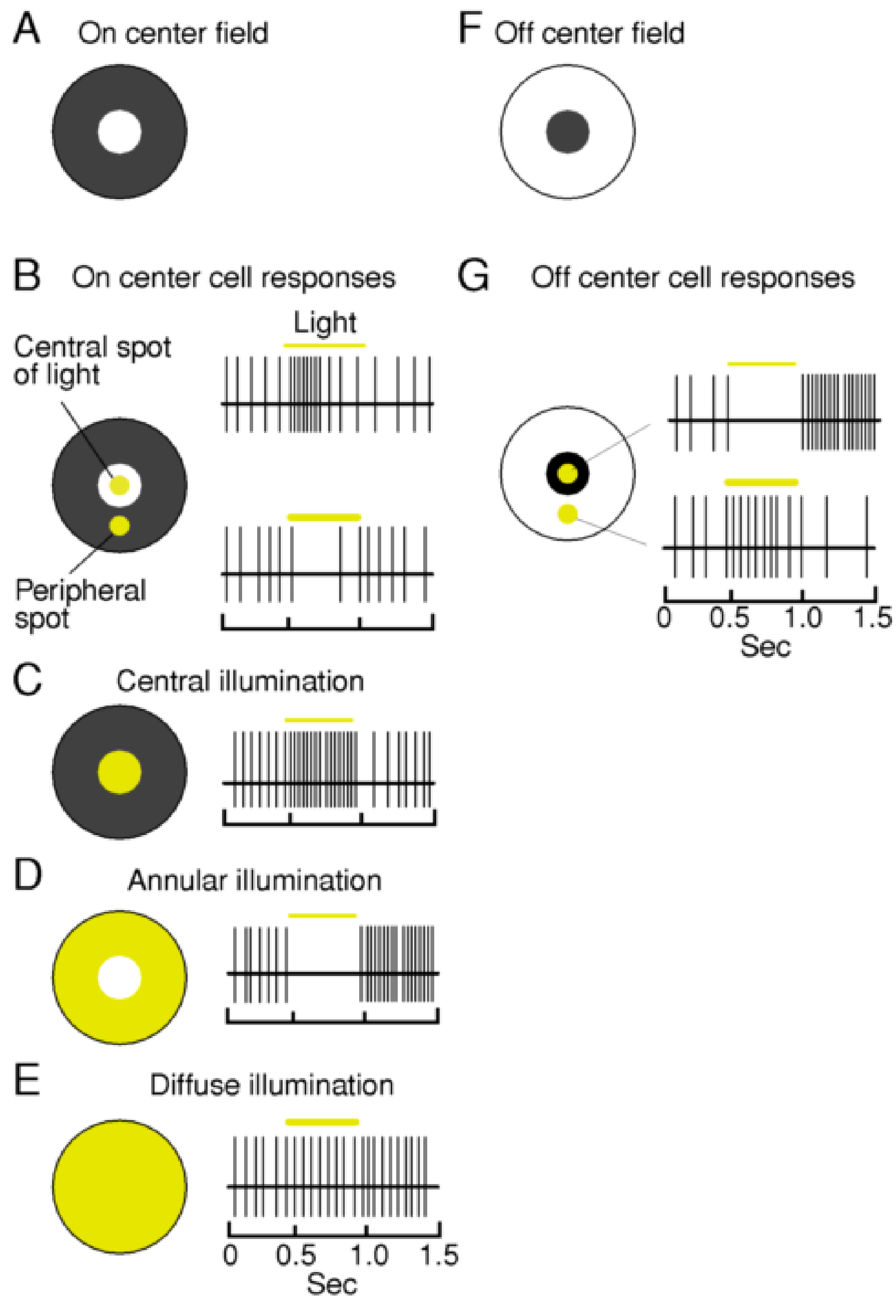
- “impedence” matching between different components
- matching to natural statistics
- matching to behaviourally relevant features
- redundancy reduction

The eye and retina

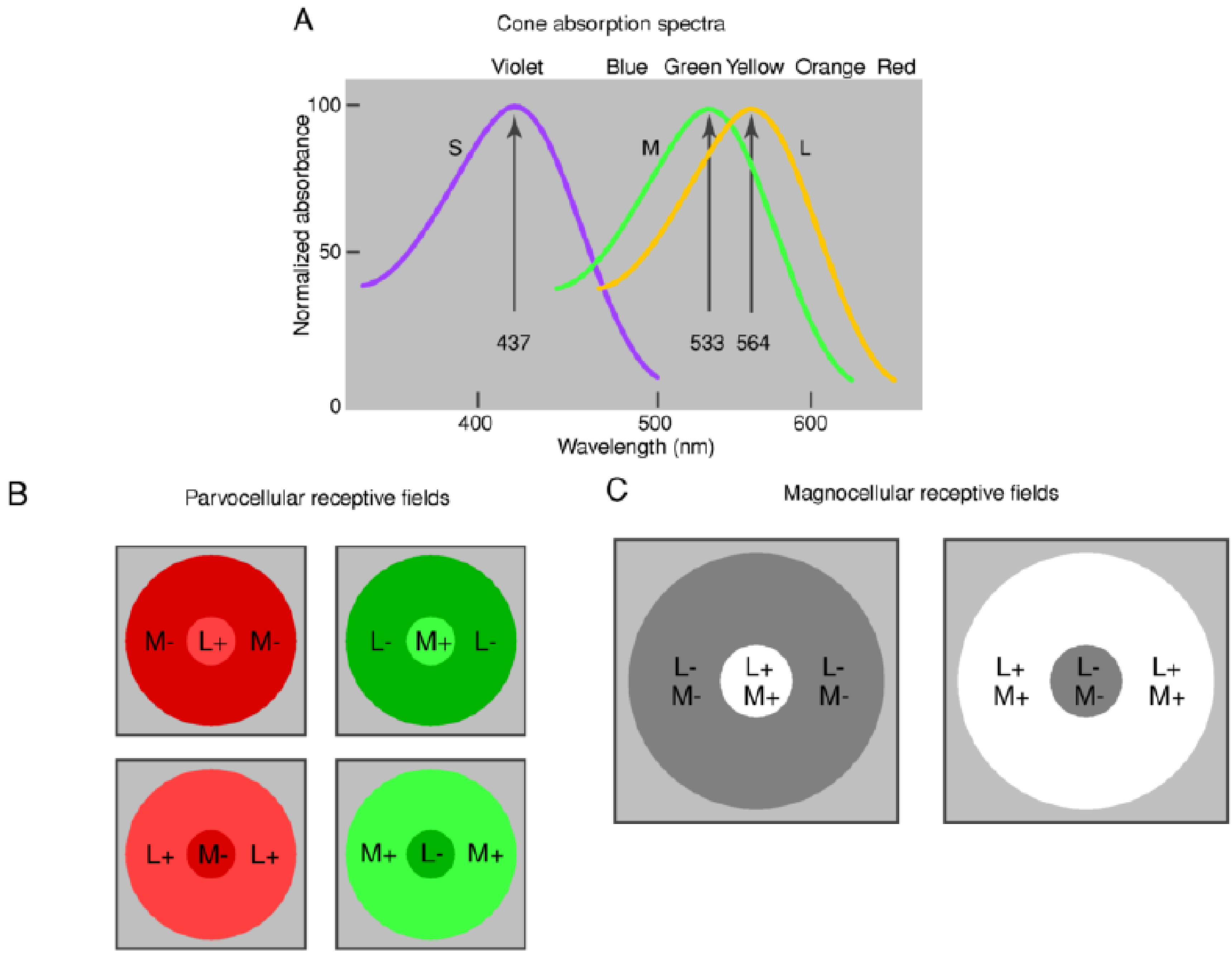




Centre-surround receptive fields



Colour at the retina

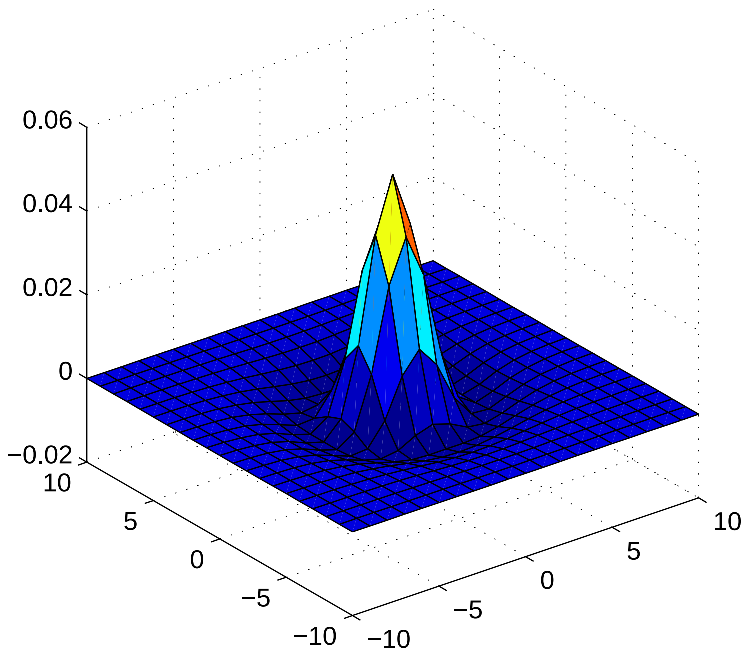


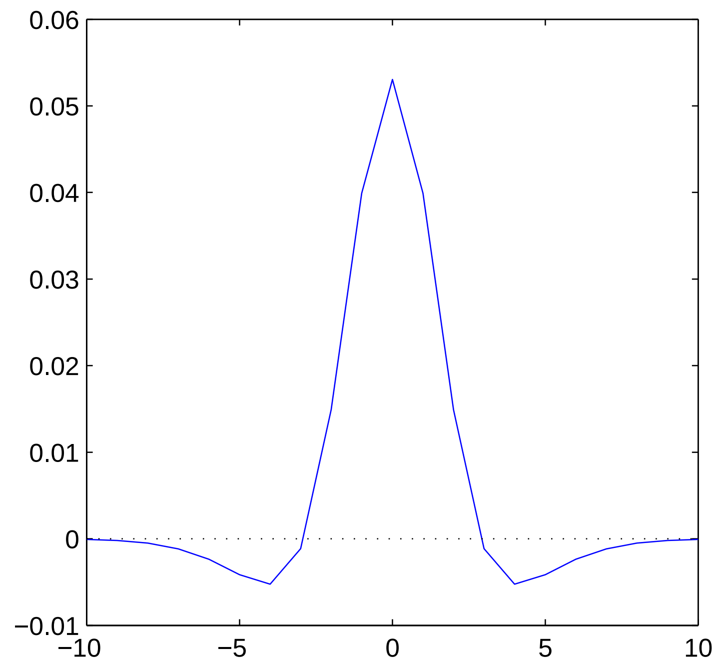
Centre-surround models

Centre-surround receptive fields are commonly described by one of two equations, giving the scaled response to a point of light shone at the retinal location (x, y).

A difference-of-Gaussians (DoG) model:

$$D_{\text{DoG}}(x,y) = \frac{1}{2\pi\sigma_c^2}\exp\left(-\frac{(x-c_x)^2+(y-c_y)^2}{2\sigma_c^2}\right) - \frac{1}{2\pi\sigma_s^2}\exp\left(-\frac{(x-c_x)^2+(y-c_y)^2}{2\sigma_s^2}\right)$$

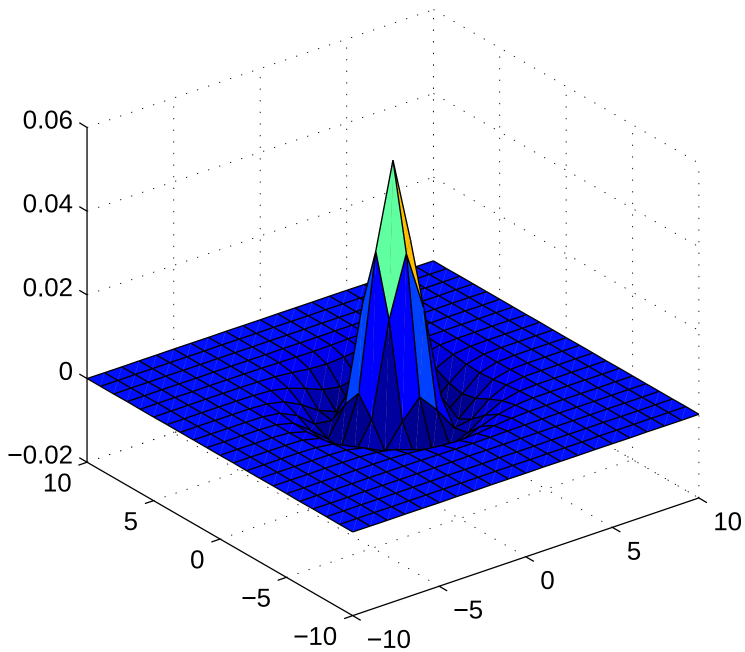


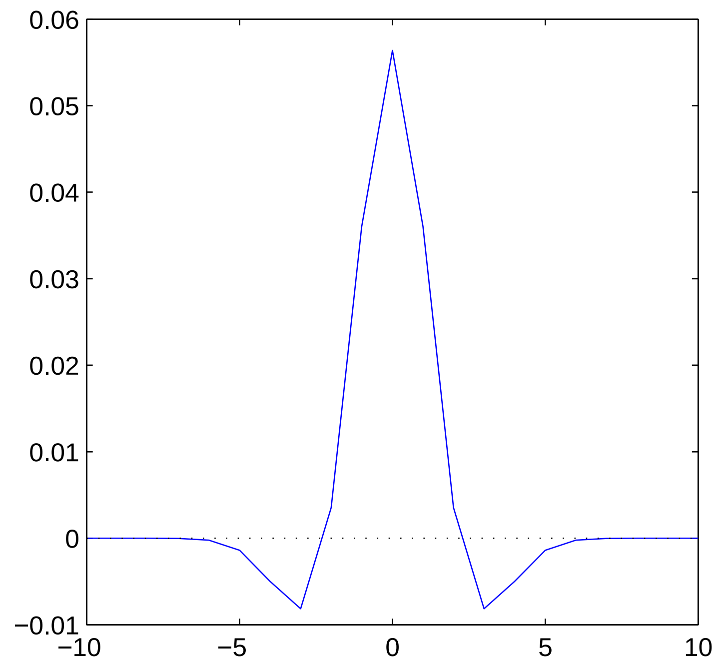


Centre-surround models

...or a Laplacian-of-Gaussian (LoG) model:

$$D_{\text{LoG}}(x, y) = -\nabla^2 \left[\frac{1}{2\pi\sigma^2} \exp\left(-\frac{(x - c_x)^2 + (y - c_y)^2}{2\sigma^2} \right) \right]$$





Linear receptive fields

The linear-like response apparent in the prototypical experiments can be generalised to give a predicted firing rate in response to an arbitrary stimulus $s(x, y)$:

$$r(s(x, y)) = \int dx\, dy\, D(x, y)s(x, y)$$

The receptive field centres (c_x, c_y) are distributed over visual space. If we let $D()$ represent the RF function centred at 0, instead of at (c_x, c_y), we can write:

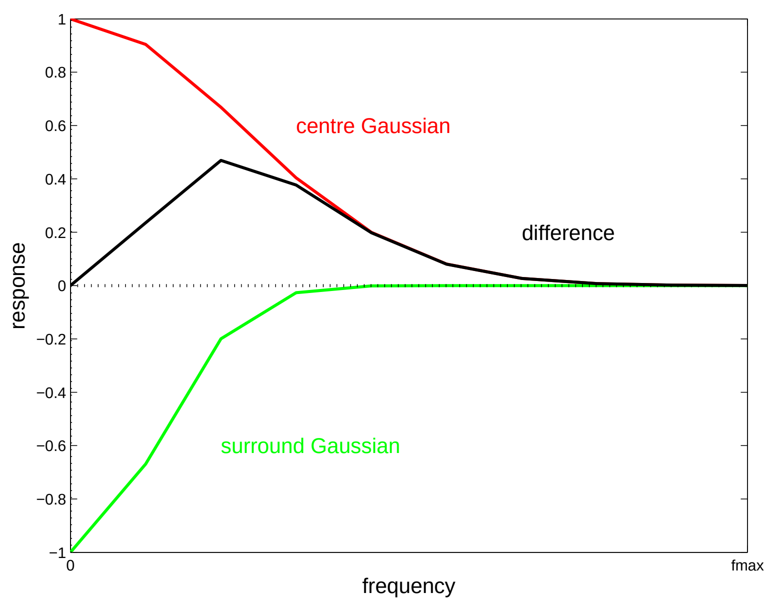
$$r(c_x, c_y; s(x, y)) = \int dx\, dy\, D(c_x - x, c_y - y)s(x, y)$$

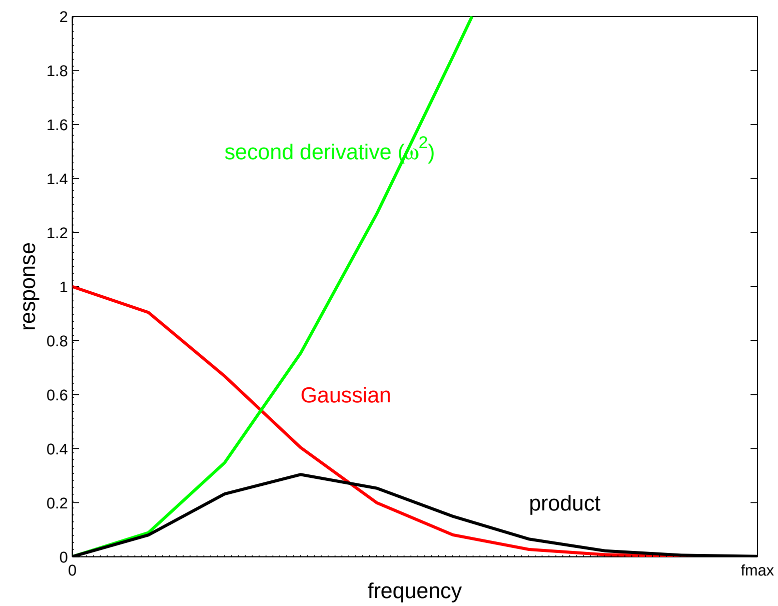
which looks like a convolution.

Frequency effects

Thus a repeated linear receptive field acts like a spatial filter. We can consider its frequency response.

Both DoG and LoG models are bandpass. Taking 1D versions:



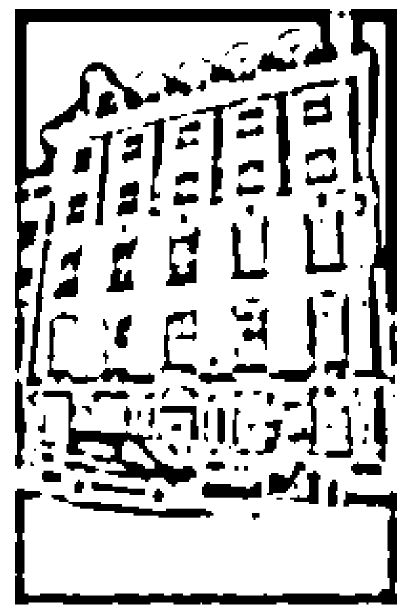


Edge detection

Bandpass filters emphasise edges:

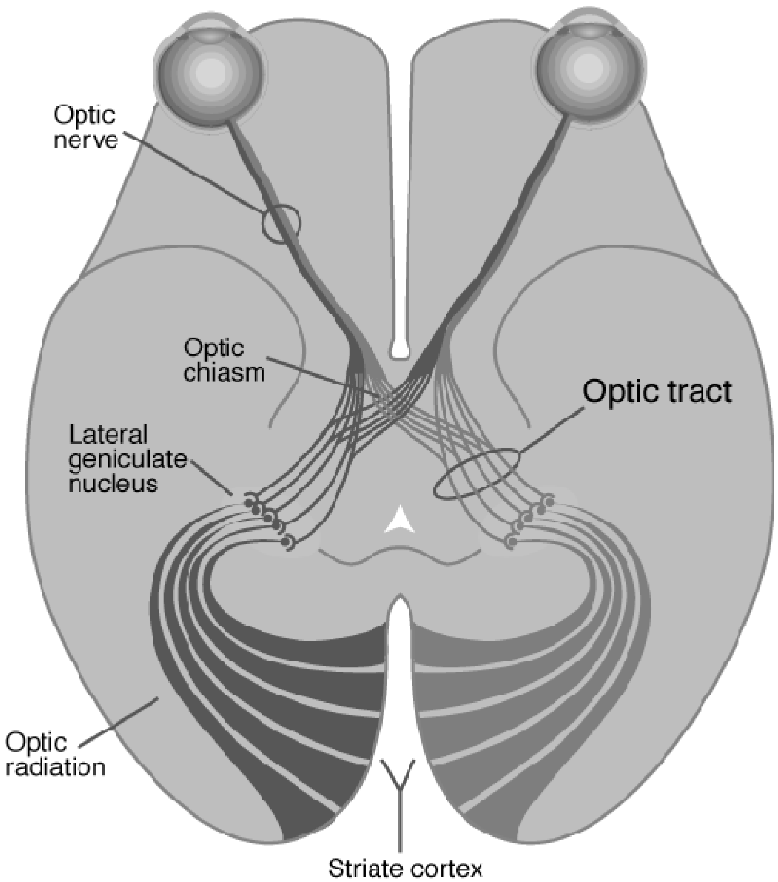
orginal image

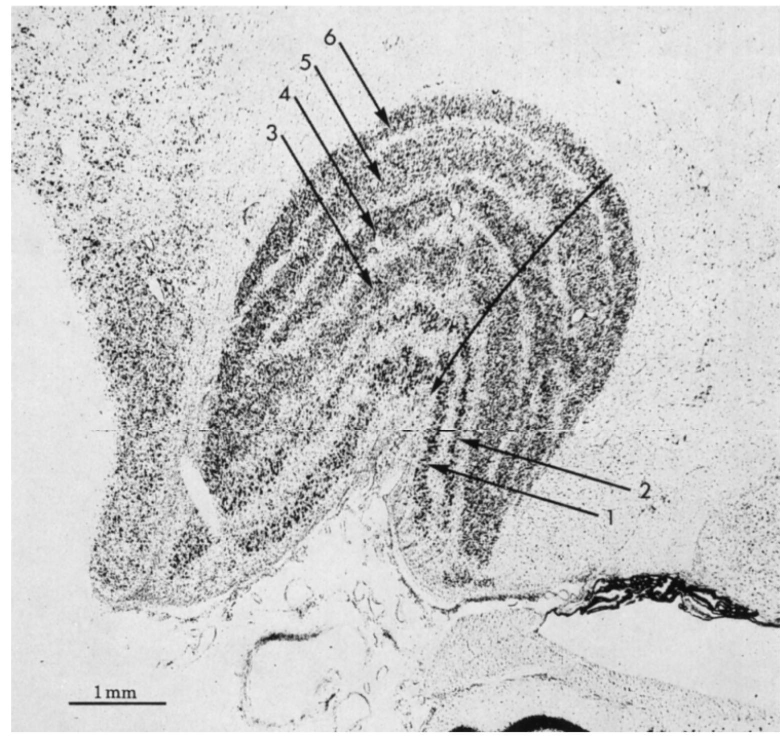
DoG responses



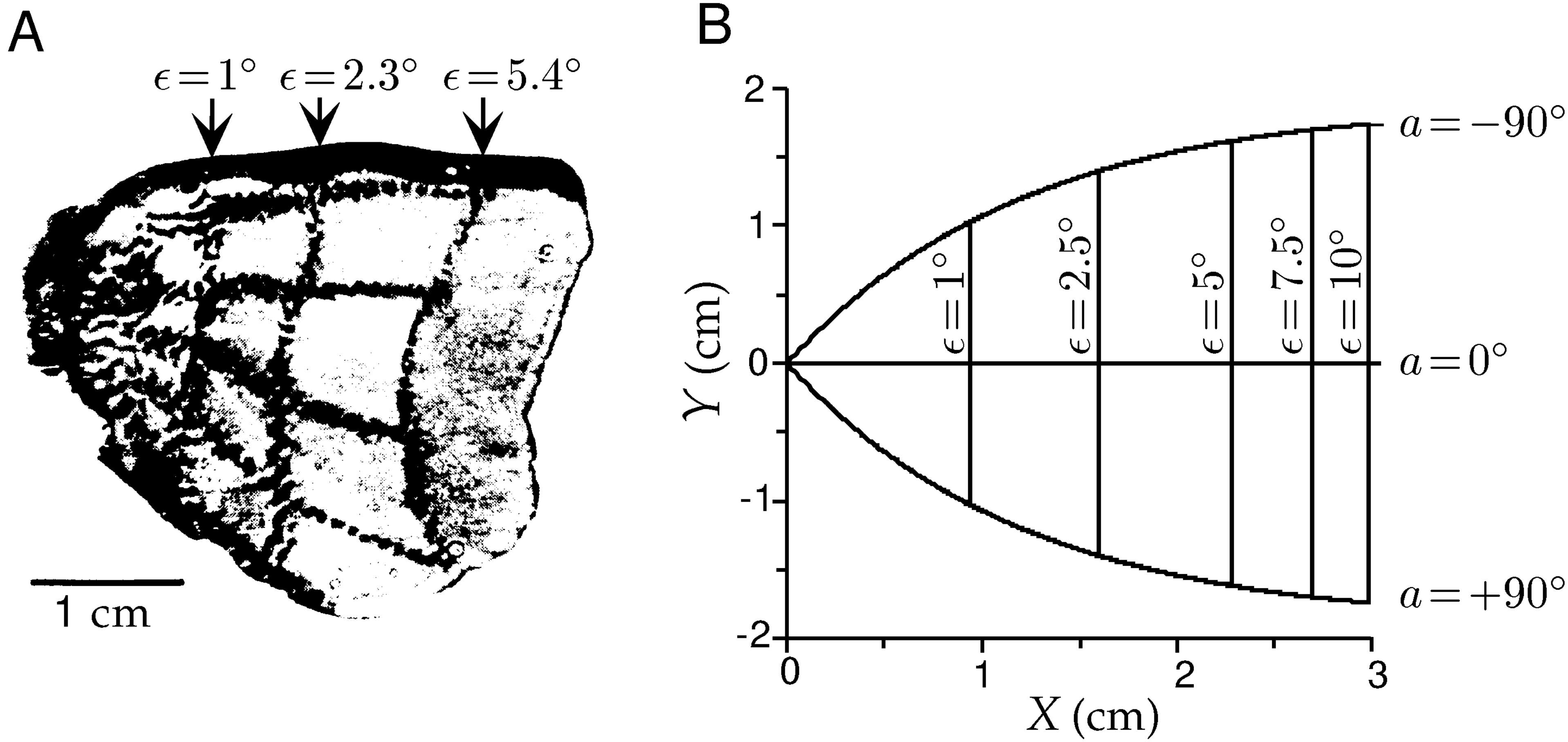
thresholded

Thalamic relay

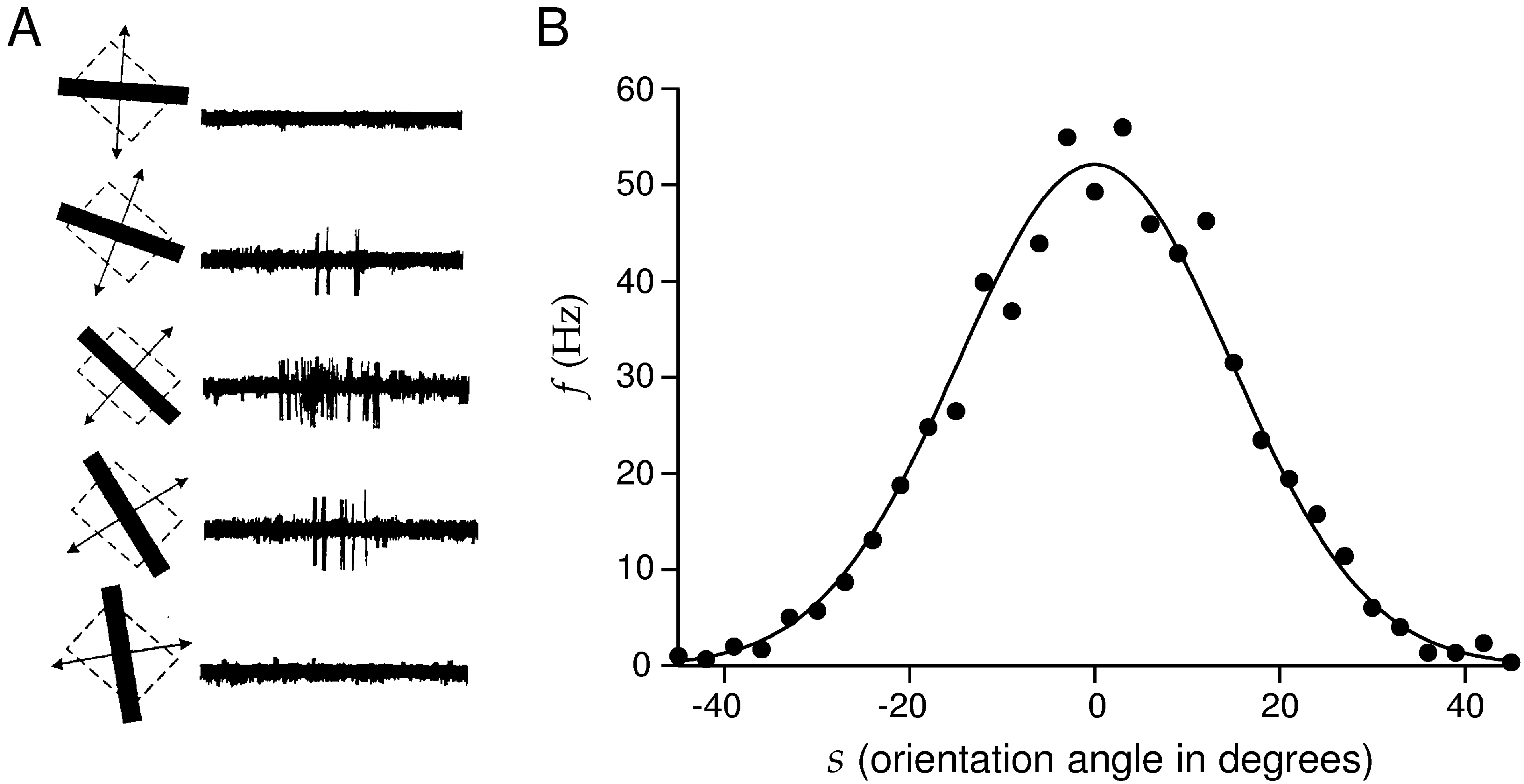




Visual cortex



Orientation selectivity



Linear receptive fields – simple cells

Linear response encoding:

$$r(t_0, s(x,y,t)) = \int_0^\infty d\tau \ \int dx \ dy \ s(x,y,t_0-\tau)D(x,y,\tau)$$

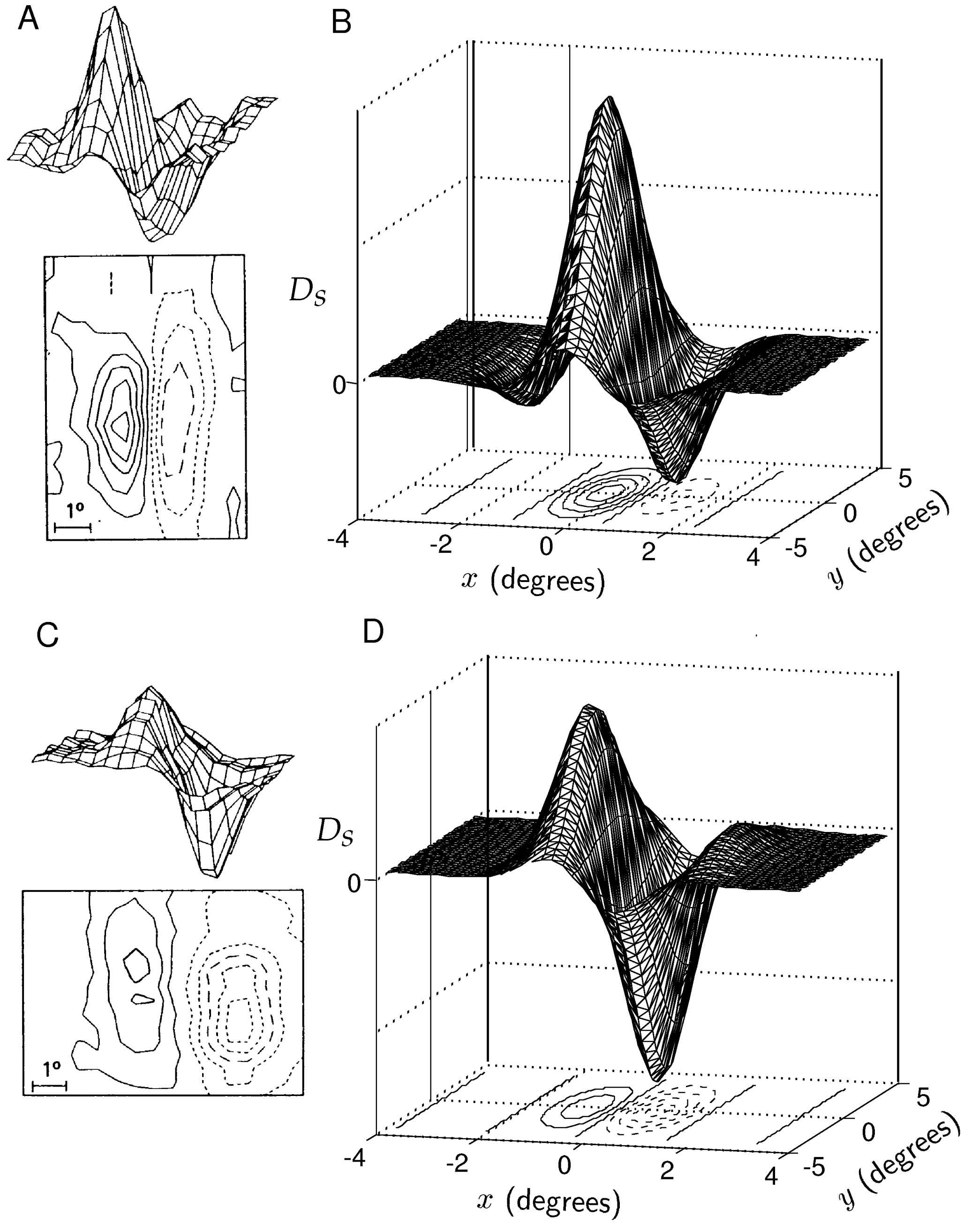
For separable receptive fields:

$$D(x,y,\tau) = D_s(x,y)D_t(\tau)$$

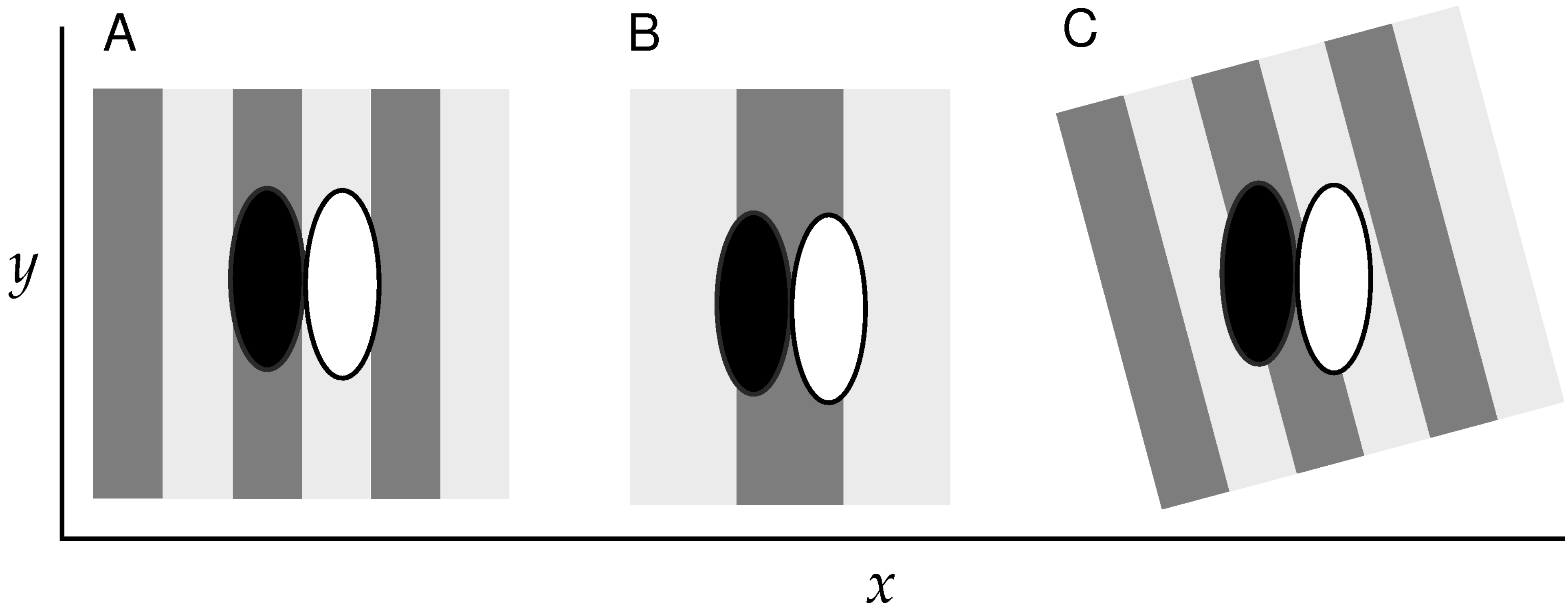
For simple cells:

$$D_s = \exp\left(-\frac{(x-c_x)^2}{2\sigma_x^2} - \frac{(y-c_y)^2}{2\sigma_y^2}\right) cos(kx-\phi)$$

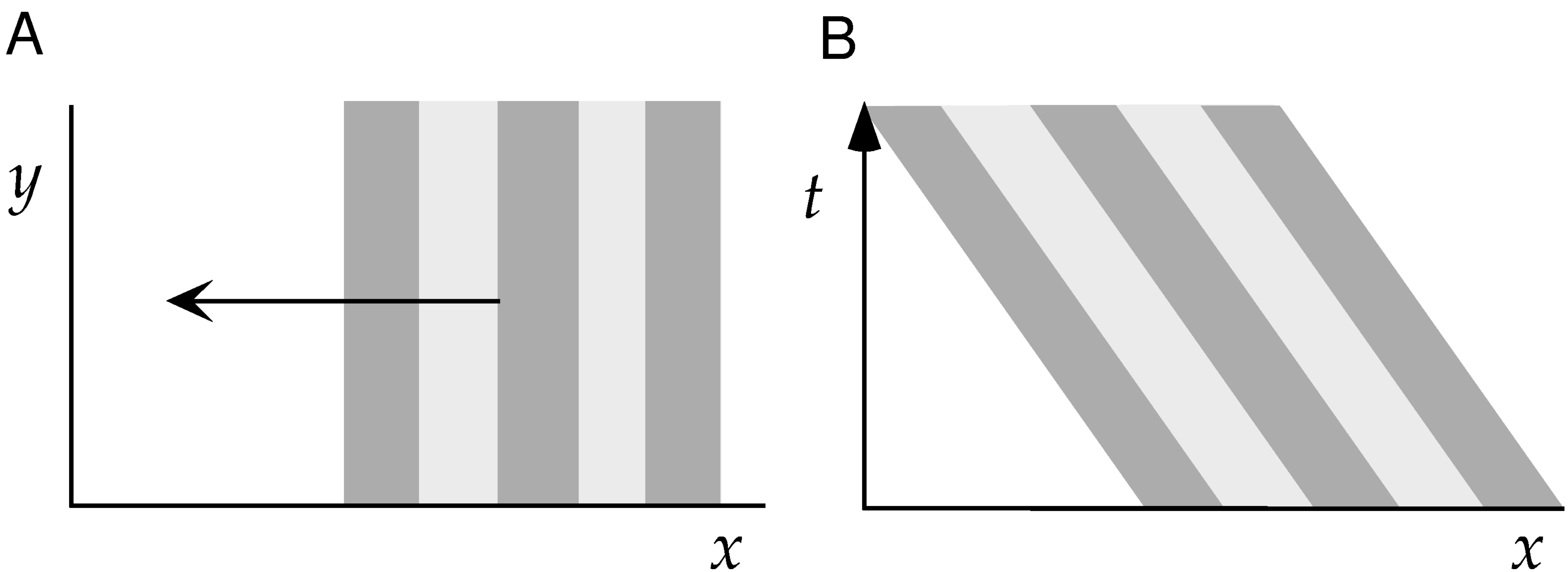
Linear response functions – simple cells



Simple cell orientation selectivity

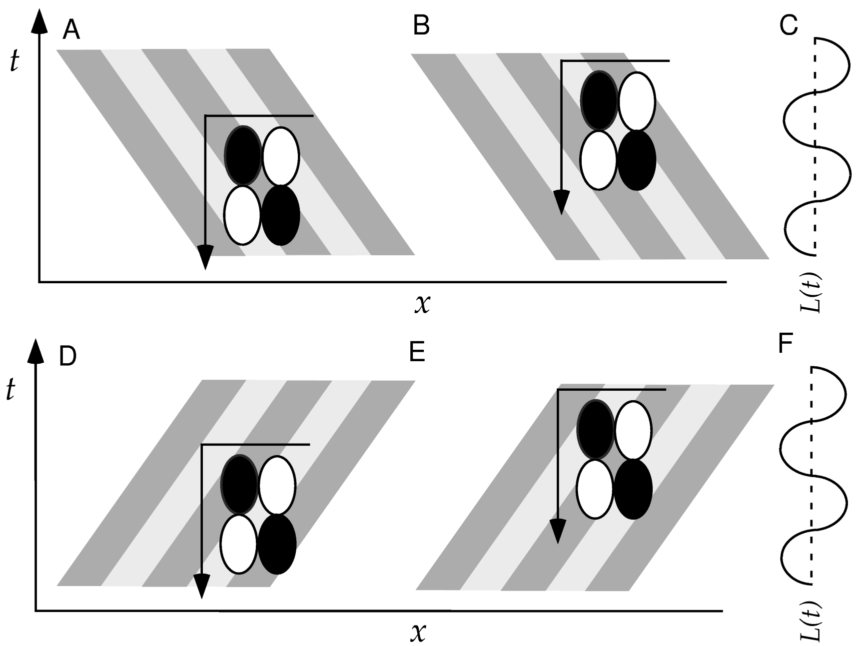


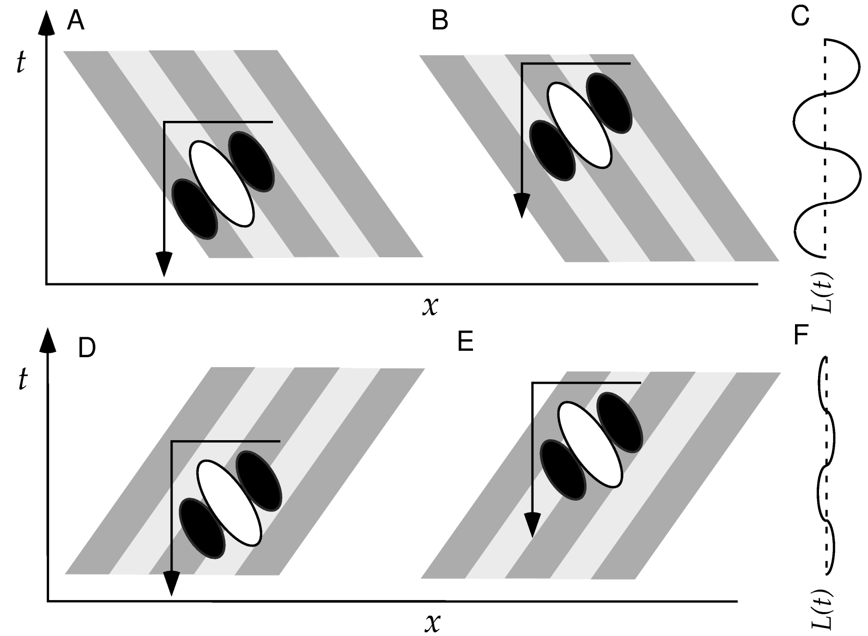
Drifting gratings



$$s(x, y, t) = G + Acos(kx - \phi)cos(\omega t)$$

Separable and inseparable response functions





Separable: motion sensitive;
not direction sensitive

Inseparable: motion sensitive;
and direction sensitive

Complex cells

Complex cells are sensitive to orientation, but, supposedly, not phase.

One model might be (neglecting time)

$$r(s(x,y)) = \left[\int dx\ dy\ s(x,y) \exp\left(-\frac{(x-c_x)^2}{2\sigma_x^2} - \frac{(y-c_y)^2}{2\sigma_y^2}\right) cos(kx)\right]^2 + \left[\int dx\ dy\ s(x,y) \exp\left(-\frac{(x-c_x)^2}{2\sigma_x^2} - \frac{(y-c_y)^2}{2\sigma_y^2}\right) cos(kx - \pi/2)\right]^2$$

But many cells do have some residual phase sensitivity. Quantified by (f_1/f_0 ratio).

Stimulus-response functions (and constructive models) for complex cells are still a matter of debate.

Other V1 responses

- end-stopping
- blobs and colour
- surround effects
- . . .

Higher Visual Areas