Computation in the Retina

Computational Models of Neural Systems
Lecture 8.1

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Spatiotemporal Ganglion Cell Model

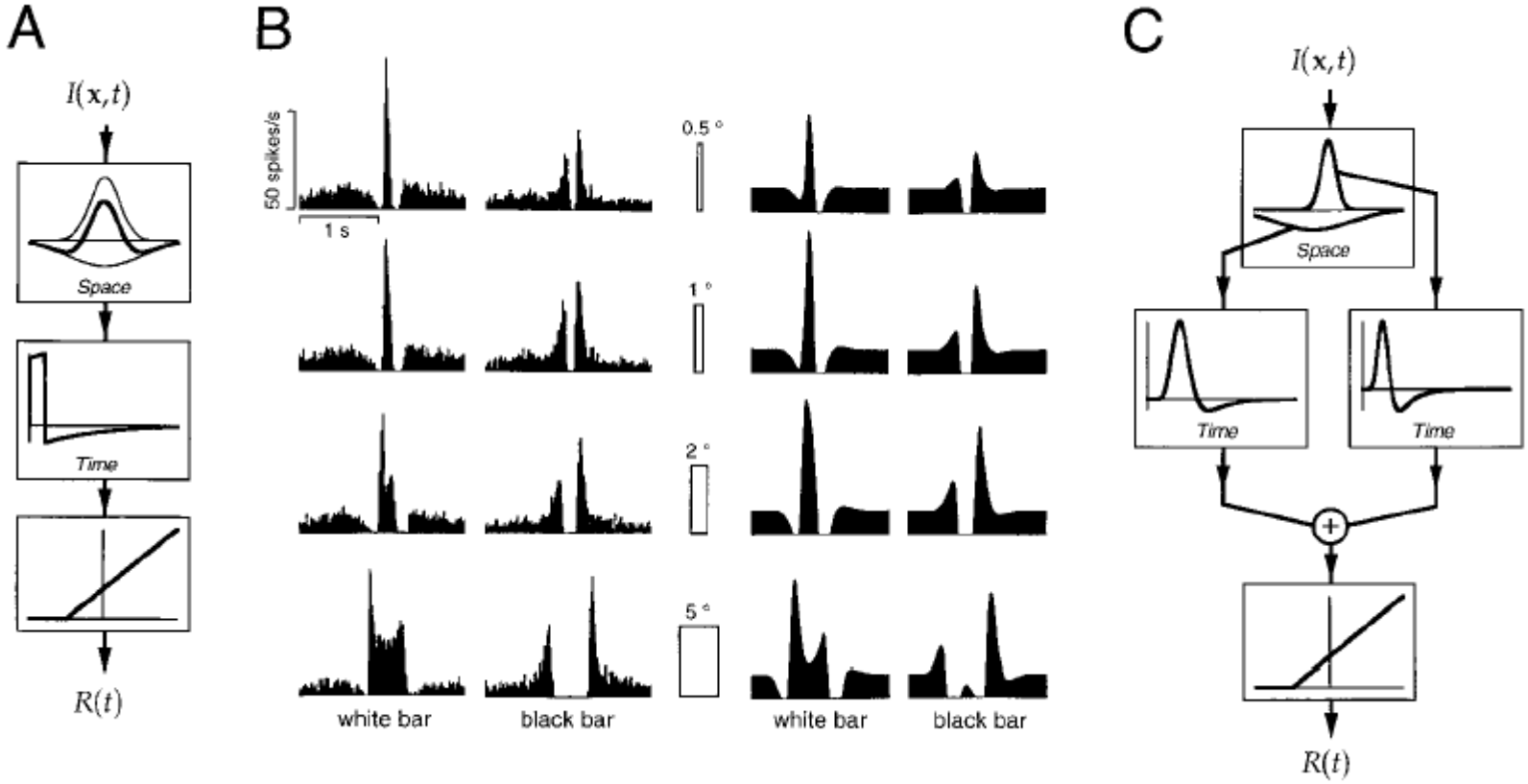
From Meister & Berry, 1999:

$$A(t) = \delta(t) - h \cdot e^{-t/\tau} \qquad \textit{temporal response}$$

$$B(x) = k_c \cdot \exp\left(\frac{-x^2}{2r_c^2}\right) - k_s \cdot \exp\left(\frac{-x^2}{2r_s^2}\right) \qquad \textit{spatial response (DoG)}$$

$$R(t) = R_0 + \int\int I(x, t') \cdot B(x) \cdot A(t - t') dx\, dt'$$

Response to Moving Bar

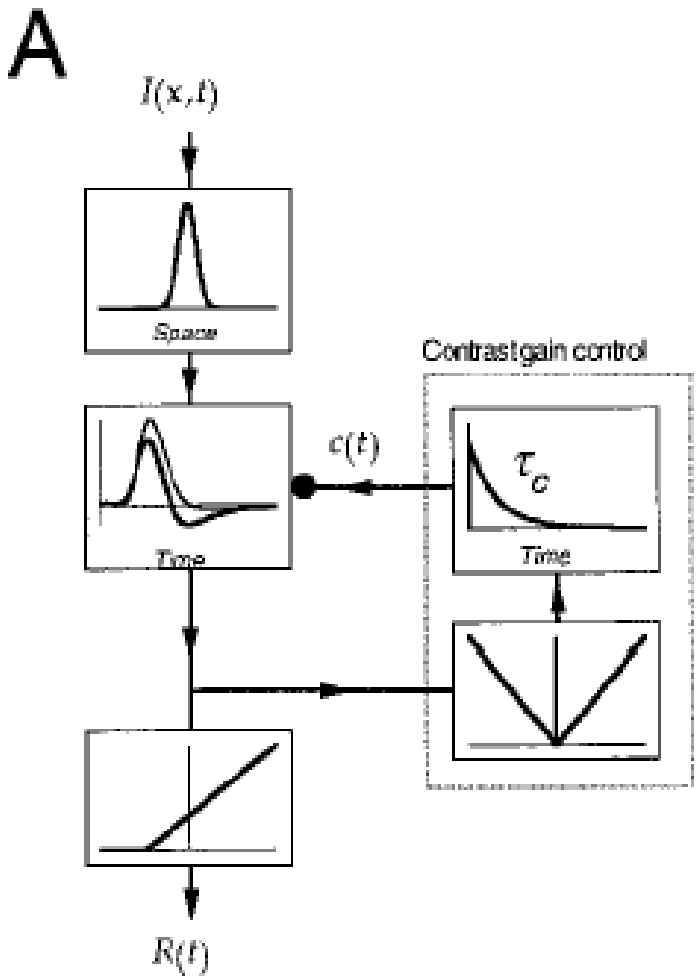


(A) Simple ganglion cell model.

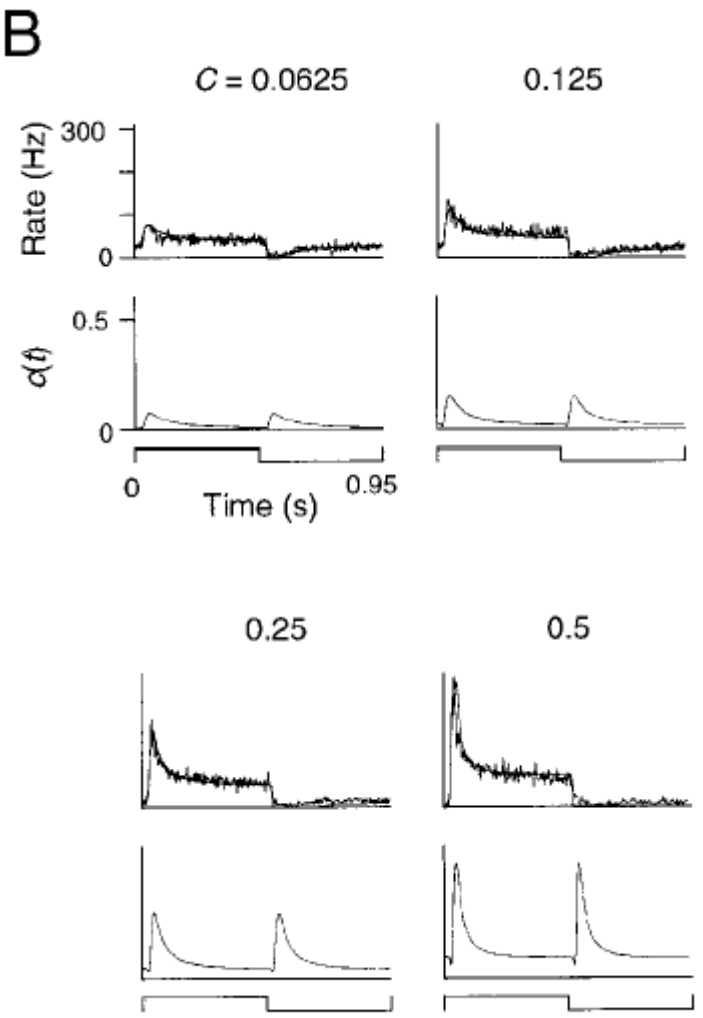
(B) Responses of cat ON-type ganglion cell, and model.

(C) Separate pathways for center and surround allows for different response parameters.

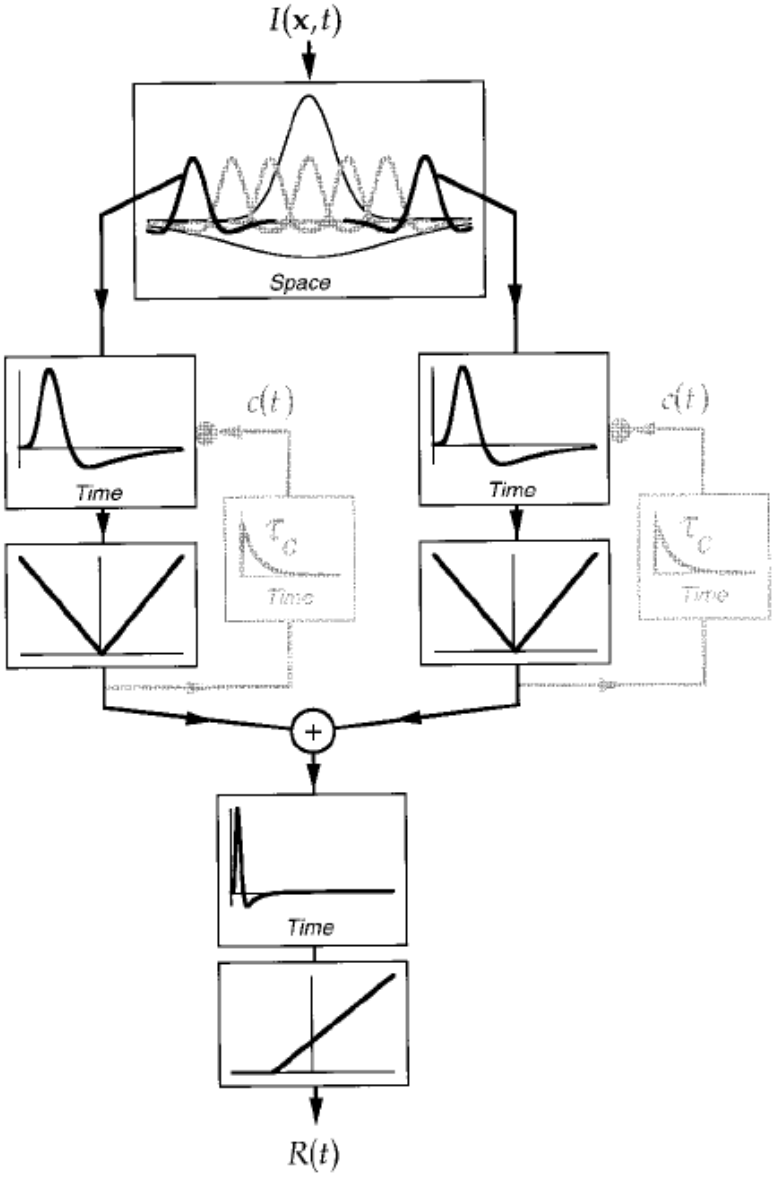
Contrast Gain Control



Cat ON-type X ganglion cell (jagged) and model response (smooth)



Cat Y Ganglion Cell Model

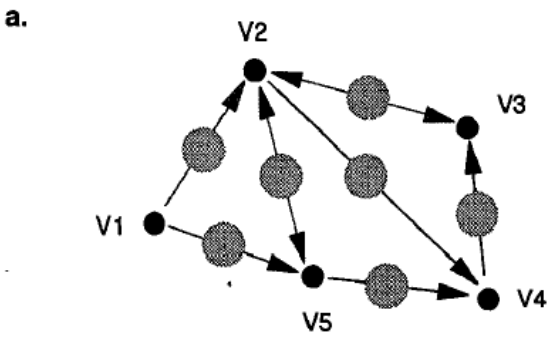


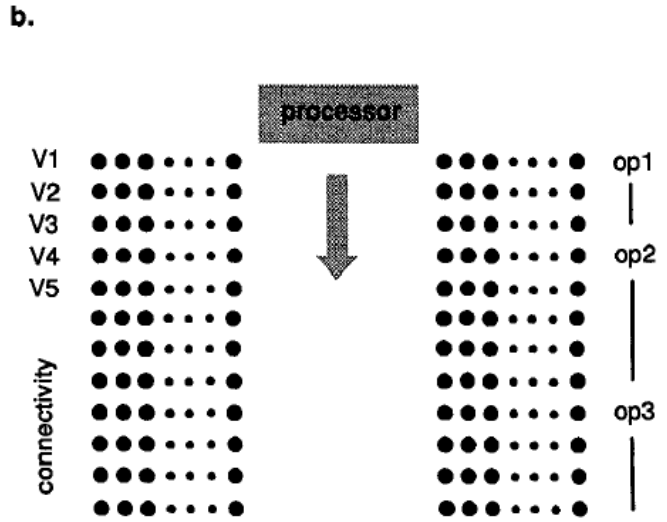
- Larger receptive field than X cell.
- Up to 100 nonlinear subunits.
- Burst of spikes at spot onset and offset.
- Poor spatial resolution, but very sensitive to moving textures.
- What are the subunits? RFs are similar to X cells.

Analog Implementation of Neural Circuits

- Pioneered by Carver Mead at Caltech
- VLSI = Very Large Scale Integration
- CMOS = Complementary Metal Oxide Semiconductor
- CMOS is a low power implementation technology for fabricating VLSI chips

Analog vs. Digital VLSI





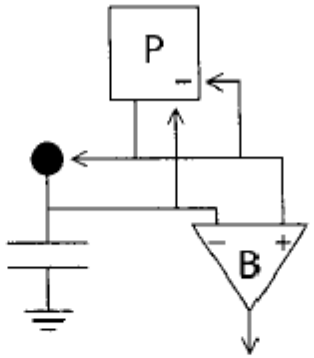
- Analog: direct analogy between circuit mechanisms and the computation being emulated.

- Digital: symbolic encoding of information and the rules for manipulating it.

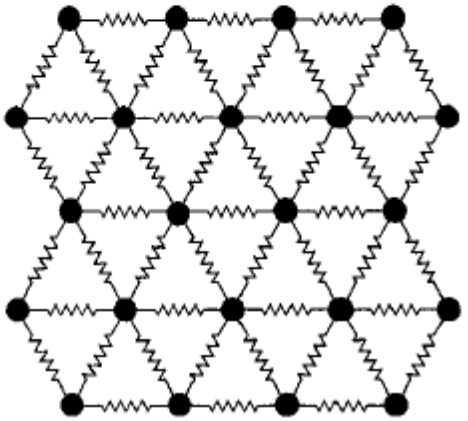
  Slower than analog, but good for multiplexing.

Early Silicon Retina Models: Mahowald and Mead

a.



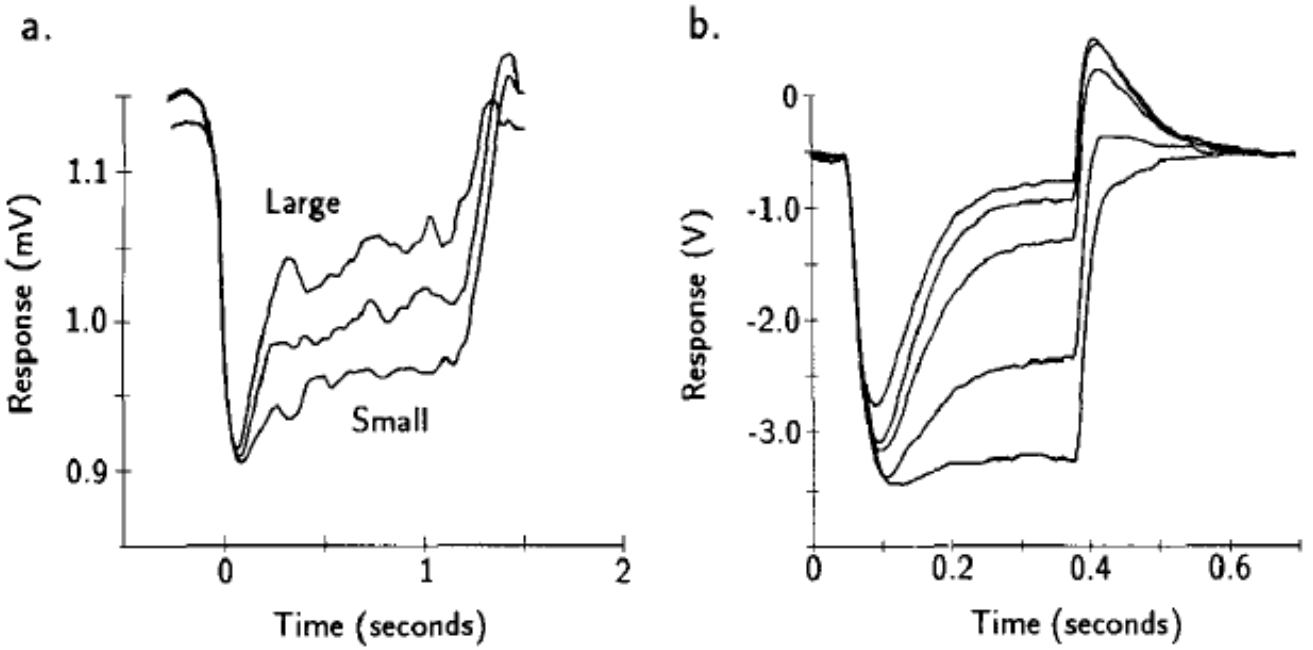
b.



- P: photoreceptor
  B: bipolar cell
  ●: horizontal cell

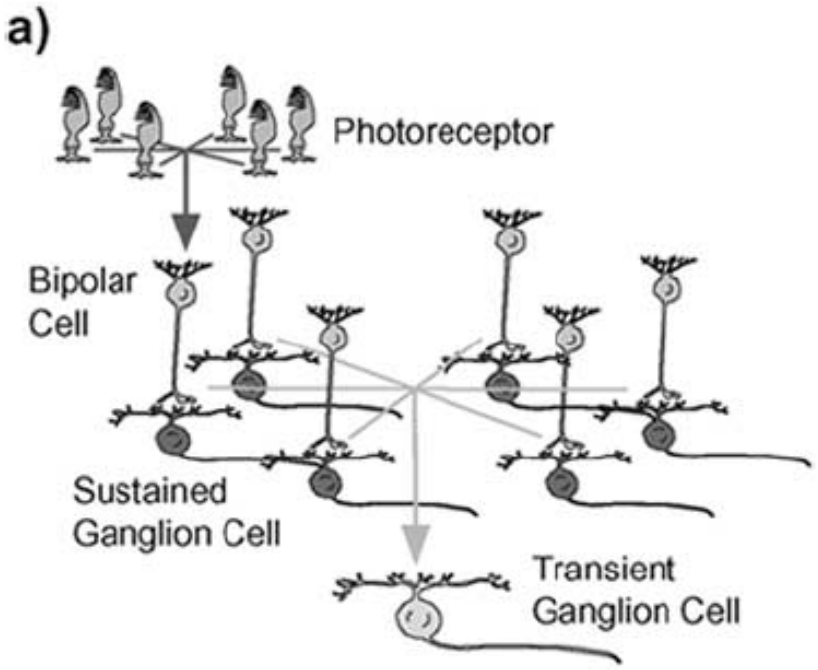
- Horizontal cells are connected to form a hexagonal resistive network, modeling the effect of gap junctions.

Response to Flashing Light Stimulus of Varying Width



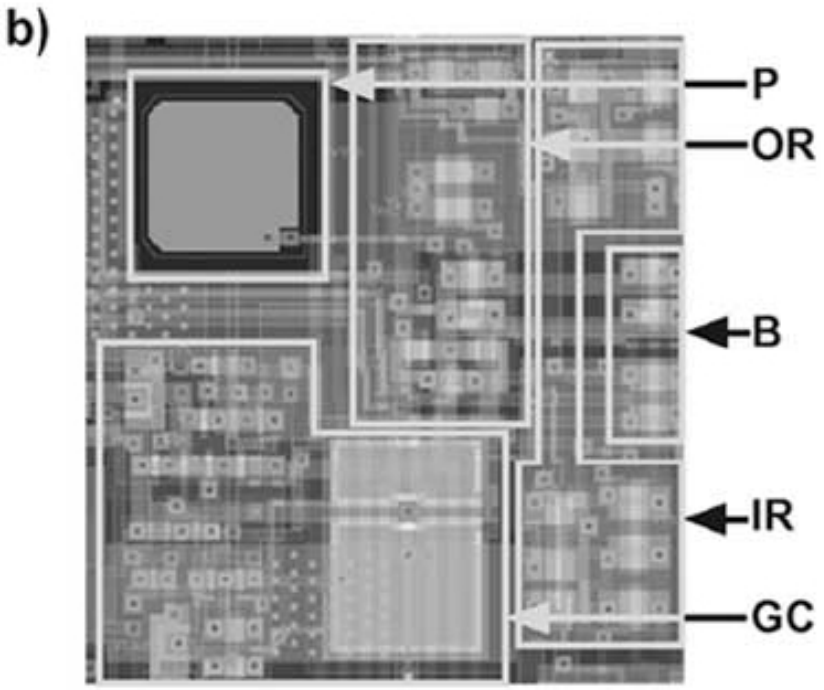
Left: bipolar cell responses in the salamander.
Right: output of a pixel in the silicon retina.

Zaghloul & Boahen (2004)



- Hexagonal array: each photoreceptor has six neighbors.
- Transient ganglion cells receive input from central photoreceptors and six neighboring sustained ganglion cells.

Pixel Layout



P: photoreceptor

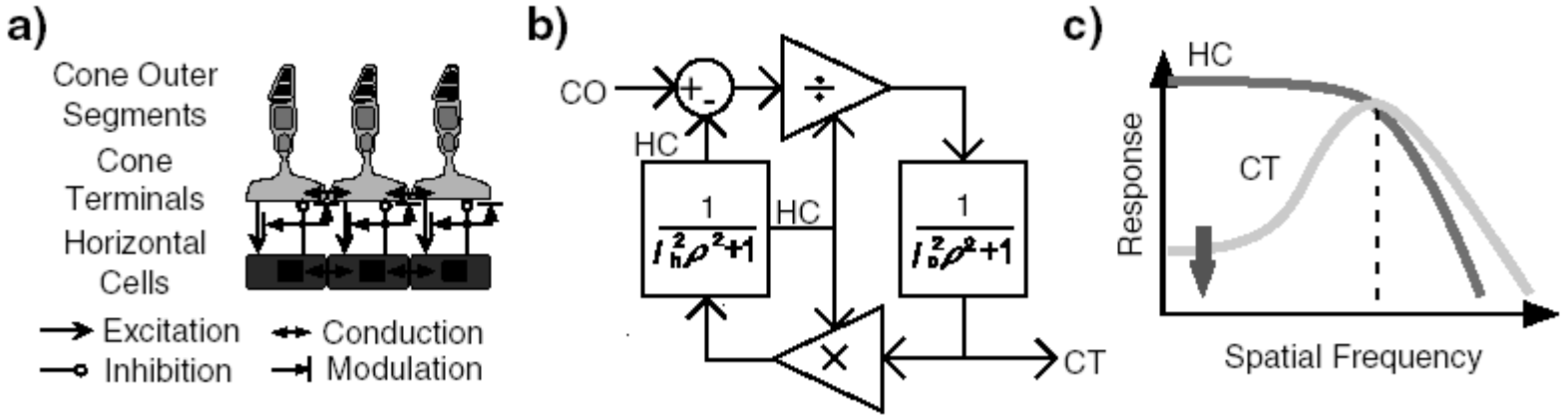
OR: outer retina circuitry

B: bipolar cells

IR: inner retina circuitry

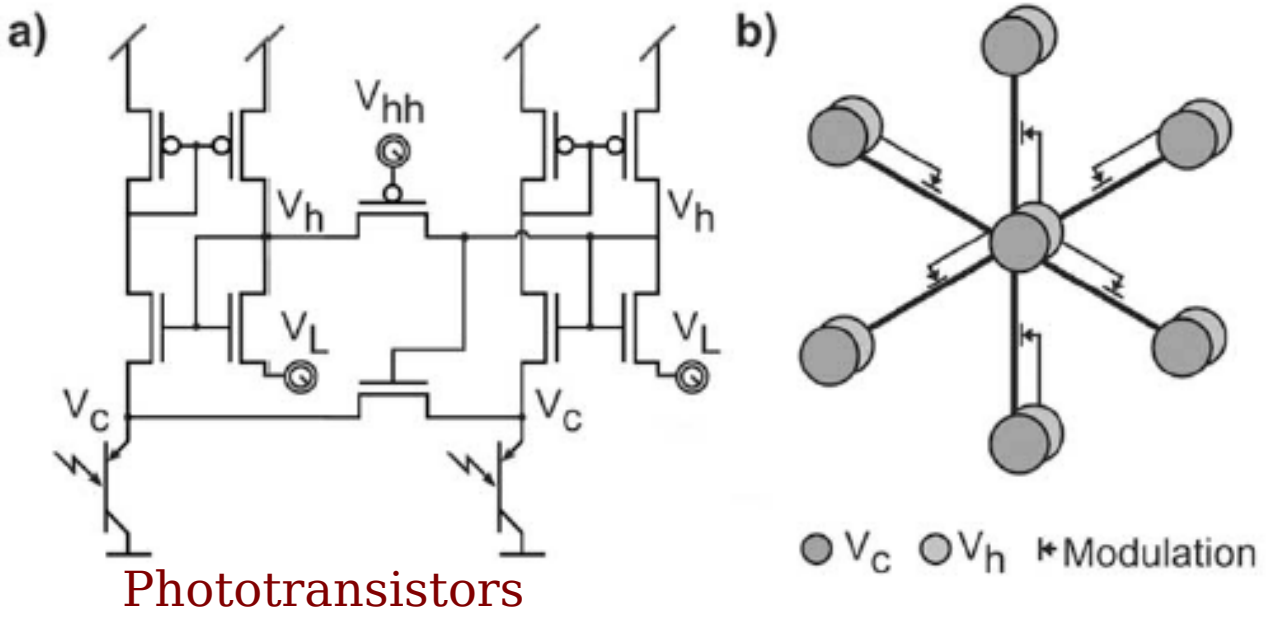
GC: ganglion cells

Outer Retina Model



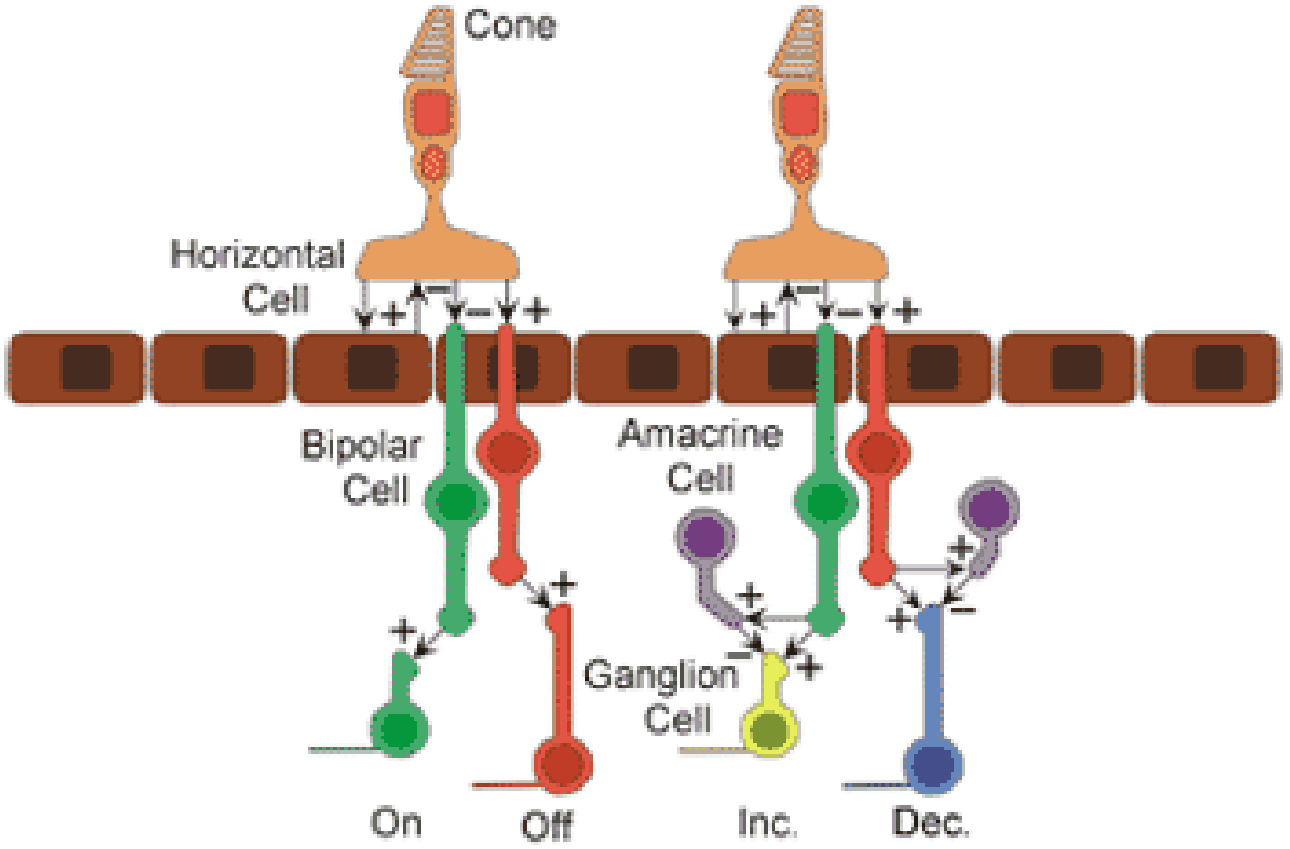
CO = cone; CT = cone terminal; HC = horizontal cell

Outer Retina Circuit



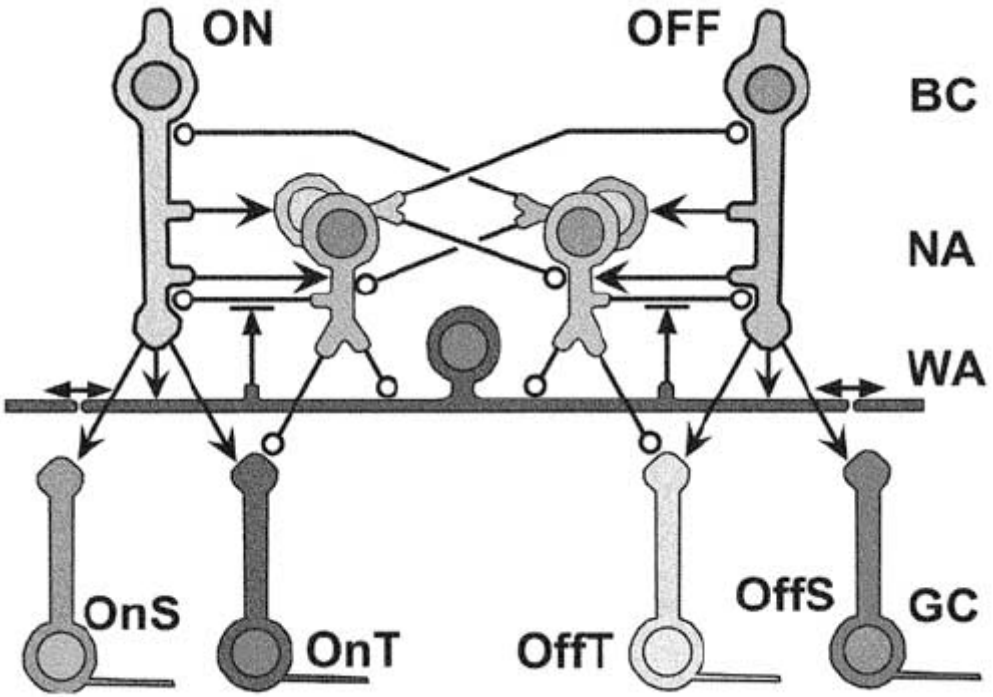
Phototransistors

Four Ganglion Cell Types



Sustained Transient

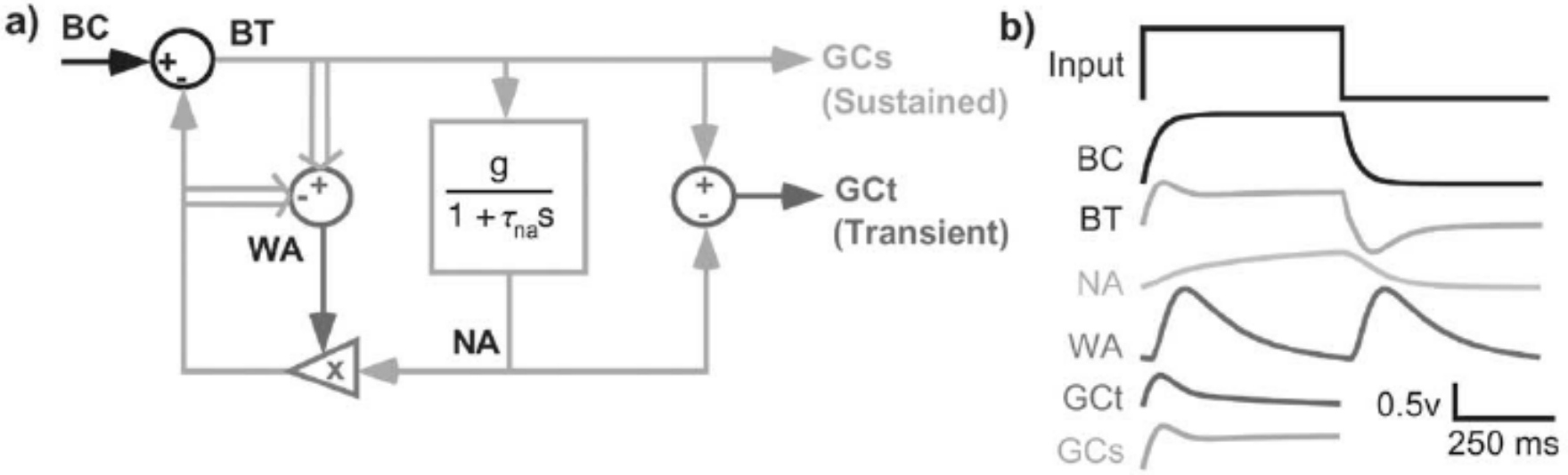
Inner Retina



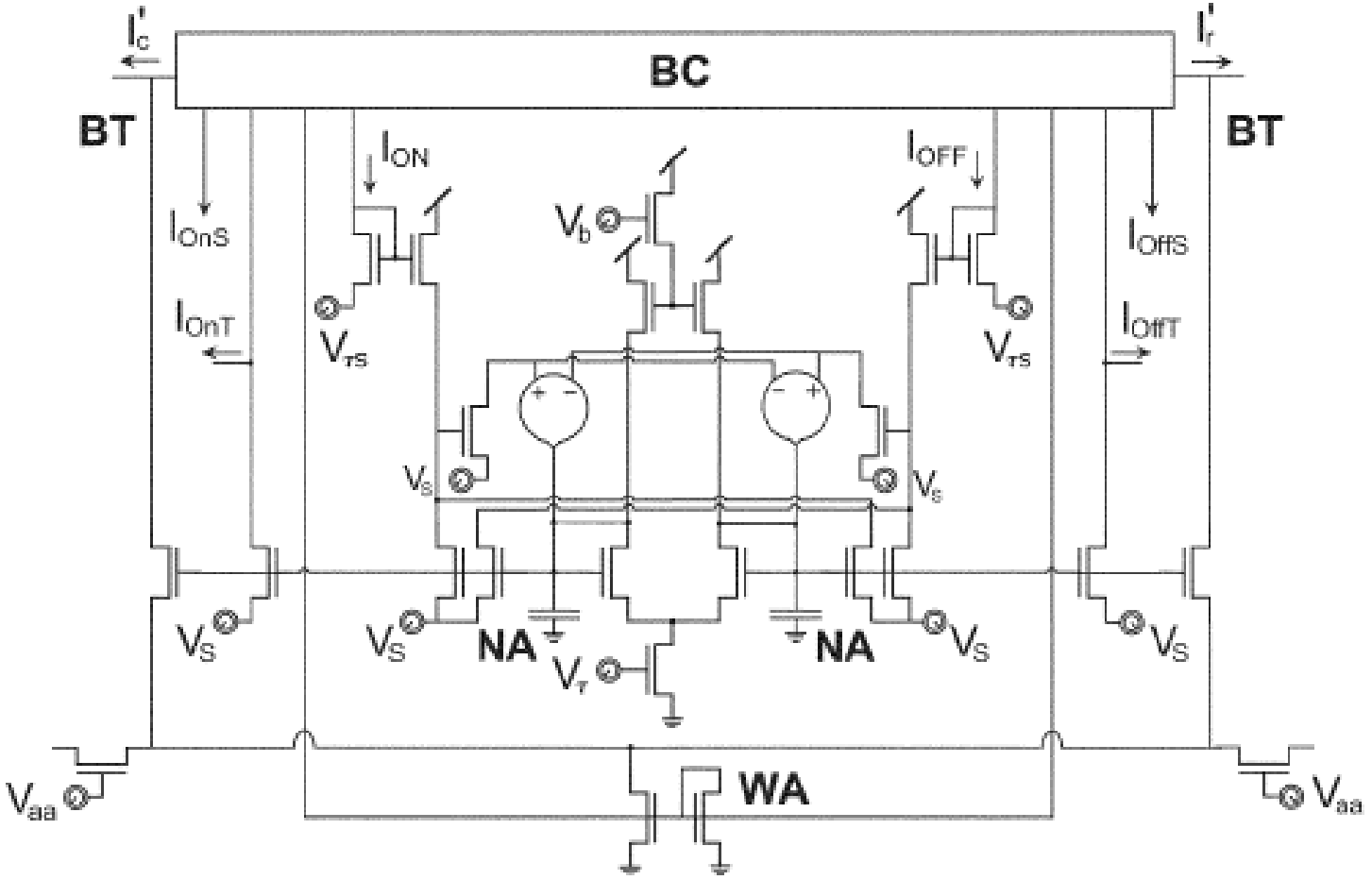
NA = narrow field amacrine cell
WA = wide field amacrine cell
BC = bipolar cell

OnS = “on” sustained ganglion cell; OnT = transient

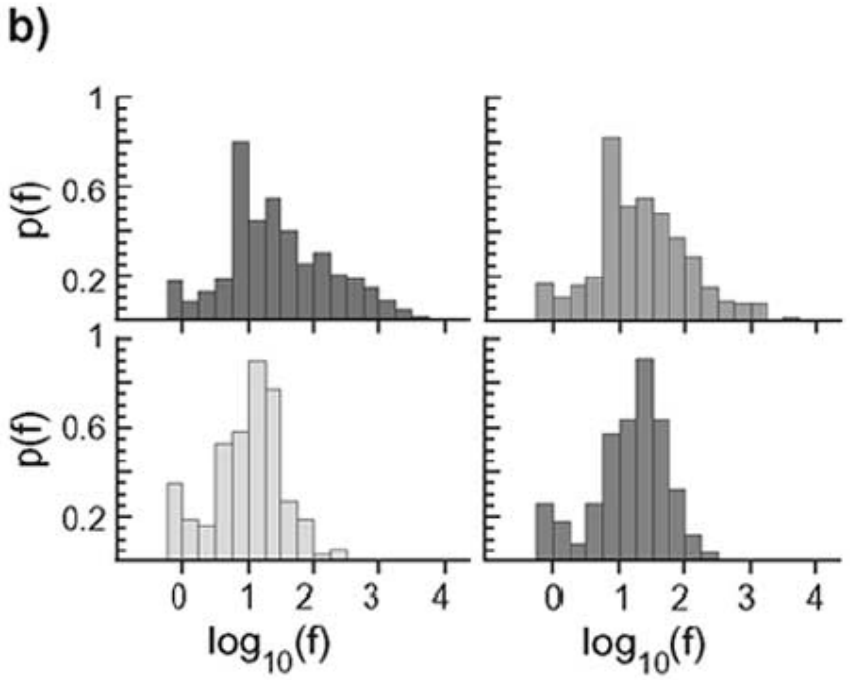
Inner Retina Model



Inner Retina Circuit

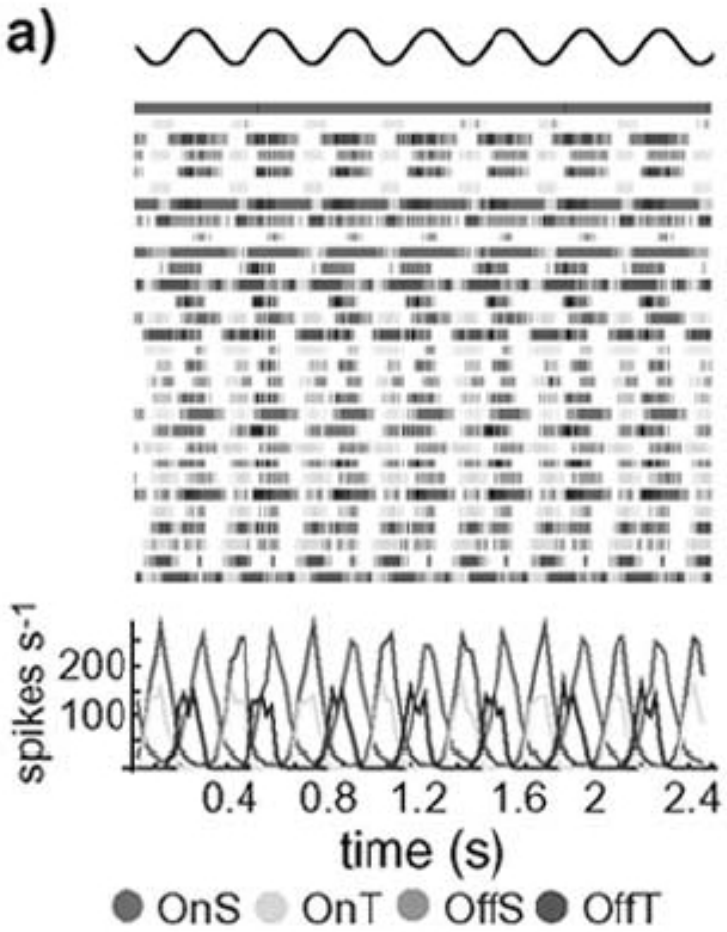


Distribution of Firing Rates



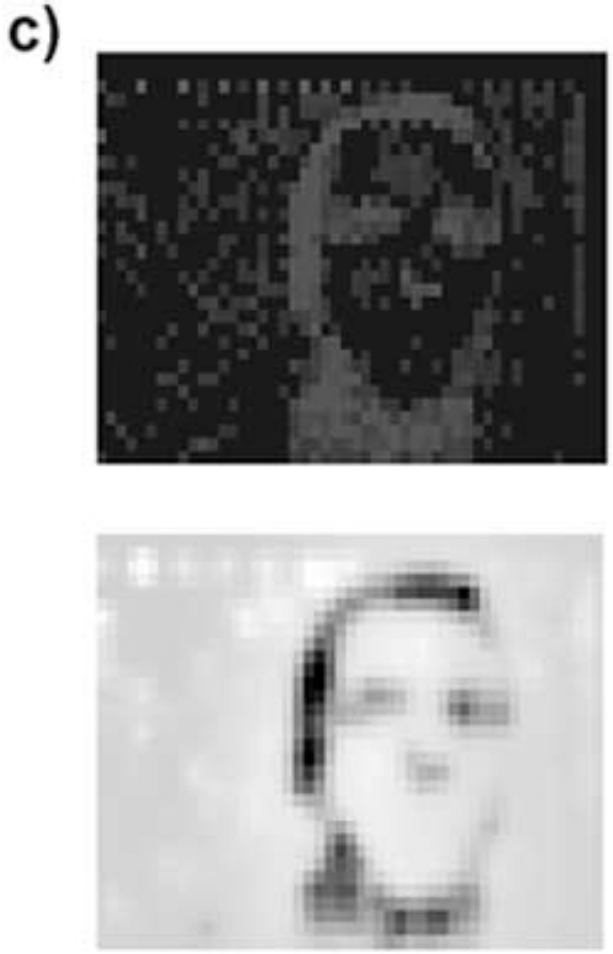
- Histogram of firing rates for the four types of ganglion cells.
- Spread shows variability in the pixels due to circuit properties and noise.

Response to Sinusoidal Grating



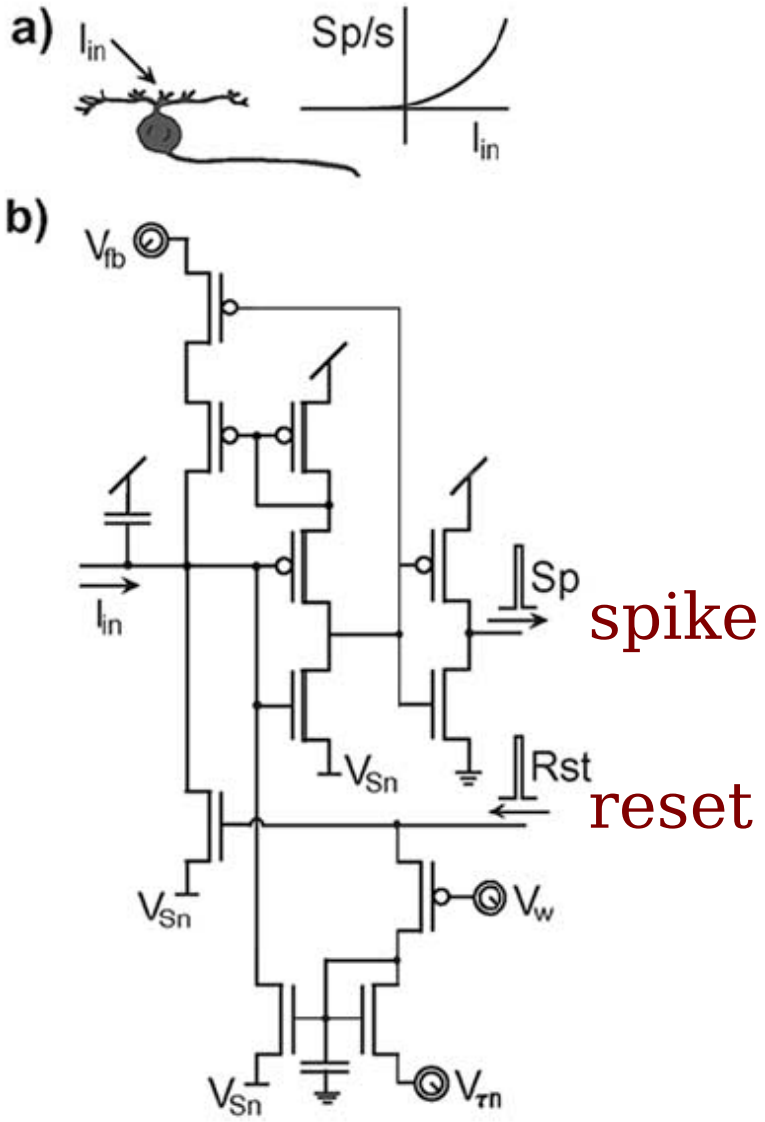
- 3 Hz 50% contrast sinusoidal grating stimulus.
- Four ganglion cell types:
  - on vs. off center
  - sustained vs. transient response

Response to Natural Images



- Top: response of four cell types to a face image.
- Bottom: image reconstructed from the ganglion cell responses.

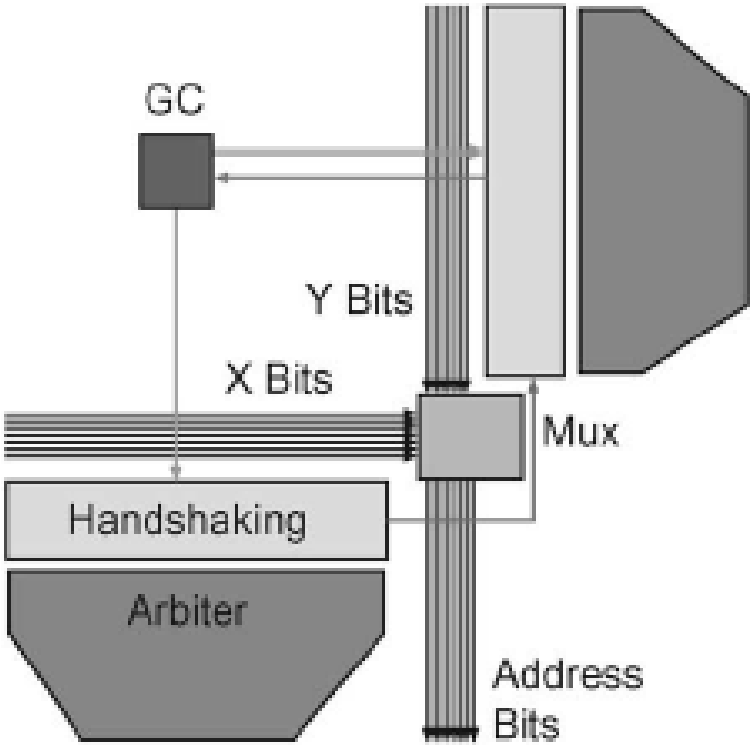
Spike Generation



CMOS circuit to generate ganglion cell spikes.

Spike rate is a function of input current.

Address Event Representation



- How to get spikes off the chip? Not enough wires.
- Solution: go digital. Each time a cell spikes, put its address on the AER bus.
- Arbitration handles collisions.