Phototransduction
Inner Life of the Cell

https://www.youtube.com/watch?v=wJyUtbn0O5Y
Dynamic range of photoreceptor: 50 mV
Steps in phototransduction

**Photoactivation:**
A photon is absorbed by a visual pigment molecule lying in one of the membranous discs contained in the outer segment.

**Biochemical cascade:**
In the dark there is a steady movement of positively charged ions (cations) into the outer segment, via ionic channels. The visual pigment molecule, activated by the photon, initiates a cascade of events that ultimately closes these channels.

**Electrotonic spread:**
Normally, the movement of cations into the outer segment is balanced by the outward movement of cations, mainly through the inner segment. The decrease in inward current creates a net outward current, which makes the interior of the cell even more negative. This hyperpolarization of the cell membrane spreads throughout the cell. This is how the information about light absorption spreads to the synaptic terminal.

**Synaptic deactivation:**
At the synaptic terminal there are calcium channels that open when the voltage across the cell membrane depolarizes and close when it hyperpolarizes. Thus the hyperpolarization of the cell membrane leads to a decrease in the rate of entry of calcium ions. Free calcium ions are continuously being removed from the cell interior, so a decrease in the rate of entry of calcium leads to a decrease in the internal concentration of free calcium ions.

**Decrease in glutamate release:**
The synaptic terminal contains vesicles that in turn contain glutamate molecules. In the presence of calcium ions, they are continuously released into the synaptic cleft. Thus a decrease in the internal concentration of calcium ions leads to a decrease in the rate of release of glutamate molecules.
Figure 8.1 Mammalian rod and fly photoreceptor amplify the energy of a single photon using different protein circuits. In both transduction schemes a photon isomerizes an opsin to activate a G protein. Thereafter the schemes diverge: the rod closes cation channels to hyperpolarize sharply (~3 mV, peaking ~125 ms); the fly photoreceptor opens cation channels to depolarize sharply (~1 mV, peaking ~20 ms). Both responses can be resolved against background noise, but the fly response is faster. N, nucleus; Gt*, activated G protein transducin; Gq*, activated Gq protein; PDE*, activated enzyme phosphodiesterase; PLC*, activated enzyme, phospholipase C; [cGMP], concentration of the messenger molecule cyclic guanosine monophosphate; [IP₃], concentration of the messenger molecule inositol triphosphate; [H⁺], concentration of protons. Rod recording is from mouse, reprinted from Cangiano et al. (2012); fly recording is from Drosophila, adapted from Niven et al. (2007).
Rhodopsin molecule

models of a rhodopsin molecule in a rod

these loops are shown spread out, they probably form more compact structures on either side of the membrane.

attachment to membrane via two lipid groups

tail of chromophore is attached to this amino acid

chromophore

α helix

amino acid

rhodopsin icon
$R \xrightarrow{\text{photon}} R^*$
Activation of rhodopsin leads to decrease in cGMP concentration occurs via four intermediate steps
Step 1: activated rhodopsin activates G-protein molecules

By means of diffusion, R* encounters an inactive G molecule.

The G_α part of the G molecule comes to lie over the exposed surface of the activated rhodopsin molecule.

As a result of interacting with R*, the GDP molecule held by the G_α portion is replaced by a GTP molecule, which converts this subunit to an activated form.

Activation of the G_α subunit, now G_α*, causes it to separate from both the rhodopsin molecule and the G_βγ portion of the G molecule.
A single activated rhodopsin molecule activates 700 G-protein molecules within 100 ms
Step 2: activated G-protein molecules bind to phosphodiesterase (PDE), exposing catalytic site
Step 3: activated PDE breaks bonds in cGMP, thus converting cGMP to GMP and lowering overall cGMP concentration.
Step 4: decrease in cGMP concentration closes channels
probability of site filled = 0.162
Photocurrent

Inward current in outer segment decreases by 0.7 pA in response to one photon of light.
Photovoltage

Charge imbalance created by photocurrent from one photon of light leads to 1 mV hyperpolarization
Synaptic terminal contains ‘ribbons’ that facilitate migration of vesicles to membrane
Neurotransmitter release

presynaptic cell

synaptic vesicle

synaptic cleft

Ca

neurotransmitter

postsynaptic cell

receptor

chemical synapse
Spontaneous isomerizations determine lower limit of light detection, or visual threshold
Chapter 8

Cone opsin supports the high release rates in bright light by binding its chromophore weakly. This makes cone opsin more vulnerable to thermal bumps, which is why a cone’s rate of thermal events exceeds the rod’s by 1,000-fold (Fu et al., 2008). Moreover, the cone’s faster transduction circuit gives more noise from spontaneous hydrolysis of cGMP. Also, the faster cGMP channel gives more noise due to state transitions in gating (Angueyra & Rieke, 2013). All sources together give the cone a dark noise equivalent to Figure 8.6.

Baboon in daylight. Photons arriving at far higher rates than starlight (figure 8.2) allow far better S/N with finer localization in space and time. For example, 10,000 photons/100 ms set an upper bound S/N ~100 by integrating over 1 μm² for 100 ms.

Because each cone in a dense array sends a private output, the brain can resolve spatial images up to 60 cycles per degree and temporal differences up to 100 Hz (chapter 11). These opportunities for high performance (S/N, acuity, and speed) are boosted by rods but best exploited by a different photoreceptor design: the cone. Reprinted with permission from Sterling (2004a). Original image from Botswana; see Tkacik et al. (2011).
How Photoreceptors Optimize the Capture of Visual Information

Figure 8.8

Chemical amplification in a mouse rod uses far less energy than electrical signaling.

Upper: Outer segment chemical processes (activation, deactivation, and recovery) are cheap and increase with light level whereas restoring ions that pass through outer segment channels is expensive and decreases with light level, given as $R^* \text{rod}^{-1} \text{s}^{-1}$.

Lower: The contribution of inner segment ion channels to total energy consumption. The cost of presynaptic calcium current declines with increasing light level, but the cost of $I_h$ current rises. Thus, the inner segment's electrical circuits consume a significant proportion of the total rod's total energy, particularly at higher light levels. Reprinted with permission from Okawa et al. (2008).