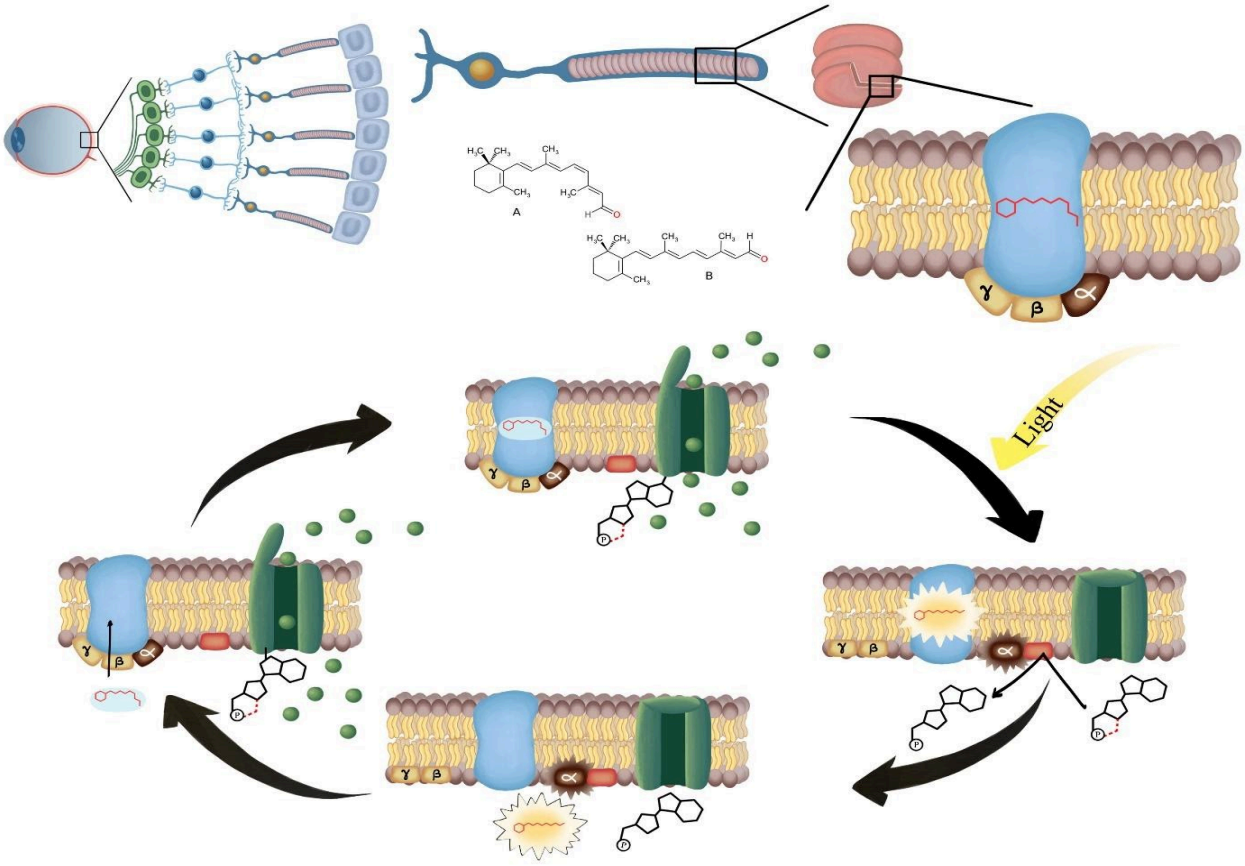
12.3.2

Phototransduction

Now for the underlying question, how do the proteins that absorb photons of light produce the action potentials that travel to the brain to produce what we perceive as vision? This process is called **phototransduction** (see figure below). Since the process is essentially the same in both the rods and the cones we will look at the rods and then explain the subtle differences that occur in the cones. It all starts with the visual pigments that are embedded in the membranes of the disks found in the outer segment of the rods. This visual pigment is called **rhodopsin** and is composed of protein called **opsin** and a derivative of vitamin A called **retinal**. In the unexcited state, retinal has a bend in its hydrocarbon chain (11-cis retinal) and fits nicely in a binding site on the opsin. When light of the proper wavelength is absorbed by the visual pigment the energy of the light causes retinal to change shape and the hydrocarbon chain loses its bend (all-trans retinal) and no longer fits in the binding site. It should be noted that even though rods provide only non-color vision, light of the green wavelength is the most efficient in activating rhodopsin. When the retina detaches from the opsin it becomes inactive. This process is known as **bleaching**. Opsin is actually a G-Protein coupled receptor (GPCR) that is activated by light, hence it is a photoreceptor. Once activated the GPCR activates the G-protein, separating the alpha subunit from the beta/gamma subunit (see module 5 for a review of GPCRs). In the photoreceptors of the eye the G-protein is called **transducin**. The alpha subunit then brings about a change in the cell. More on this later.



Phototransduction. *Created by BYU-Idaho student Hannah Crowder, 2013*
Phototransduction. The top image represents the photoreceptor in the dark. The green channel is the cGMP gated cation channel which is open and allowing cations (Na^+ and Ca^{++}) to depolarize the cell. When light strikes and changes the retinal from 11-cis to all-trans retinal it activates the G-protein transducin which results in the breakdown of cGMP and the closing of the cation channel. The cell will then hyperpolarize. Finally, All-trans retinal is converted back to 11-cis retinal and it re-attaches to opsin allowing cGMP to open the cation channel and once again depolarize the cell.

Photoreceptors are different than any receptors we have discussed to date in that they release neurotransmitter when they are **not** being stimulated. Here is how this works. There are three important ion channels in the membranes of the photoreceptor cells, **K^+ leak channels, voltage-gated Ca^{2+} channels** and **cyclic GMP (cGMP) gated cation channels** (Na^+ and some Ca^{2+} move through this channel). When the photoreceptor is not being stimulated (in the dark), cGMP is bound to the cation channel and Na^+ and Ca^{2+} diffuse into the cell maintaining it in a depolarized state. This depolarization causes the voltage gated Ca^{2+} channels to open, allowing more Ca^{2+} to diffuse into the cell. This Ca^{2+} triggers the release of the neurotransmitter glutamate by the process of exocytosis. The binding of glutamate to receptors on the bipolar neurons may be excitatory or inhibitory; it depends on what receptors are expressed on the bipolar neuron. In this module, we will focus on just the bipolar neurons that express receptors that cause **inhibition** when glutamate is attached.

When light is absorbed by rhodopsin and the G-protein (called transducin) is activated, the alpha subunit of the G-protein activates the enzyme **phosphodiesterase**. This enzyme breaks down cGMP to GMP. Once the cGMP is removed the cGMP-gated cation channels close and the membrane hyperpolarizes. This results in the closing of the voltage-gated Ca^{2+} channels and glutamate release ceases. Removal of the inhibitory signal to the bipolar neurons allows them to fire and an action potential is sent to the brain. Eventually, the G-protein is inactivated and phosphodiesterase is turned off. However, the rhodopsin cannot respond to light again until the retinal is returned to its bent, 11-cis, state. To do this, it diffuses into the pigment epithelium where enzymes act to restore the 11-cis state. It can then diffuse back into the rod cell and bind to opsin. The rod cell is ready to be activated again. The original bleaching process is very fast, fractions of seconds, but restoring the rhodopsin to its intact state can take several minutes. During the day, when we are exposed to sufficient light, the rhodopsin remains in the bleached state and the rods are essentially unresponsive to light. The mechanism is similar in the cones. The main difference is in the proteins of the visual pigment. The visual pigments in cones are similar to rhodopsin but they respond to different wavelengths of light allowing us to perceive different colors. Another difference, as stated above, is that the cones are much less sensitive to light. This is why the cones do well in full daylight when everything is brightly illuminated. Finally, cones do not stay deactivated (bleached) as long as rods. Cones appear to be fairly resistant to large scale “bleaching” as they are able to recover 11-cis-retinal much more quickly so that at any given time there are at least some visual pigments ready for stimulation.

Recall that the axons of the ganglion cells form the optic nerves. These nerves enter the brain through the optic canals of the skull. As they move posteriorly they converge at a point just above the hypothalamus called the optic chiasm (the word chiasm comes from the Greek letter Chi or X, implying a point of crossing over). In the optic chiasm some of the axons cross to the opposite side of the brain while some stay on the same side. Let’s see if we can make sense of this. If we use the fovea as a reference point we can divide the retina into two halves, a lateral or temporal half and a medial or nasal half. Axons originating on the lateral retina enter the optic chiasm but do not cross over while those from the medial retina cross over to the opposite side of the brain. What are the implications of this? Suppose you are looking straight ahead and light from an image at your right enters your eye. It will be focused on the lateral retina of your left eye and the medial retina of your right eye. Since axons from the lateral retina do not cross over while axons from the medial retina do cross over, the image will be projected to only the left hemisphere of your occipital lobe. An object to your left would be projected to only your right hemisphere and the object directly in front of you would go to both hemispheres. The overall result of this interesting circuitry is that it tells us how far away the objects are, in other words, it is responsible for our depth perception. Try closing one eye and judging how far you are from an object. You can do it but it is more difficult and less accurate.

From the optic chiasm, the optic nerves project to the thalamus where they synapse with the neurons that connect to the primary optic cortex in the occipital lobe of the cerebrum where it is perceived as an image. It is interesting that what we perceive isn't always what our eyes see. For example, as you gaze around the room everything seems like it is in sharp focus. The reality is that our eye is only capable of producing sharp vision on a very small portion of our visual field. If you hold your thumb at arm's length in front of you, the area covered by your thumbnail is about all the eye can focus sharply. Why then does everything seem clear? It is because our brain makes us think it is clear. Try focusing on something and then pay attention to the things on either side. They will not be in sharp focus but you didn't notice that until you thought about it. In reality, much of what we see is a product of our brains and not necessarily what the eye is seeing. For proof of this statement watch or listen to the TED talk below about, but beware they may blow your mind.

https://books.byui.edu/-Rxv (Transcripts available with videos website)