TOURO COLLEGE & UNIVERSITY SYSTEM

The Science Journal of the Lander College of Arts and Sciences

Volume 3
Number 1 *Spring 2010*

2010

The Nerve Cells of the Retina

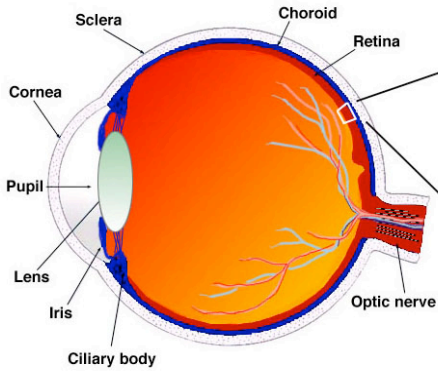
Penina Winkler
Touro College

The Nerve Cells of the Retina

Penina Winkler

Abstract

The visual pathway in the retina consists of a chain of different nerve cells. Light first travels through all the layers until it reaches the photoreceptor layer, the rod and cone layer. Rods and cones use photopigments, which contain opsin and a chromophore, to help them convert light into energy. This energy is then passed on to the horizontal and bipolar cells. Horizontal cells prevent the hyperpolarization of peripheral rods and cones if needed, and they receive color-coded signals from cones that they then continue along the optic pathway. Bipolar cells can be divided into rod bipolar cells and cone bipolar cells. Cone bipolar cells can be further subdivided into midget cone bipolar cells, which only contact one cone cell and one ganglion, and diffuse cone bipolar cells, which can contact several cone and ganglion cells. Bipolar cells can either hyperpolarize or depolarize with light, and they pass their signal on to amacrine cells or ganglion cells. Amacrine cells provide inhibition to the visual pathway, either through feedback inhibition on the bipolar cells or feedforward inhibition on ganglion cells. A1 amacrine cells provide long-range inhibition of ganglion cells. Indoleamine-accumulating amacrine cells provide a reciprocal response to bipolar cells, preventing them from hyperpolarizing so that their signal does not continue. AII amacrine cells receive input from bipolar cells and output the signal to different bipolar cells to be transmitted to ganglion cells. Ganglion cells, the last nerve cells in the visual pathway, only receive input when light hits the part of the receptive zone that produces a discharge when stimulated by a light source. Ganglion cells are specialized to detect movement in a specific direction. This prevents the brain from receiving unnecessary information. EphrinA and EphrinB are two molecules that form gradients that lead the ganglion cells to their specific destination in the brain. Magnocellular (MC) ganglion cells and intrinsically photosentive retinal ganglion cells (ipRGCs) are specific types of ganglion cells, with MC cells dominating during fixational eye movements, and ipRGCs working as circadian photoreceptors like rods and cones, contributing to light-stimulated effects on the body. Müller cells are not part of the visual pathway, but they provide support for the retina and regulation of nutrients and molecules, as well as perform many other functions in the retina.



(Kolb H. et. al. 1996)

Penina Winkler, BS '09 graduated Touro College with her degree in Biology. She will be attending pharmacy school in the fall.

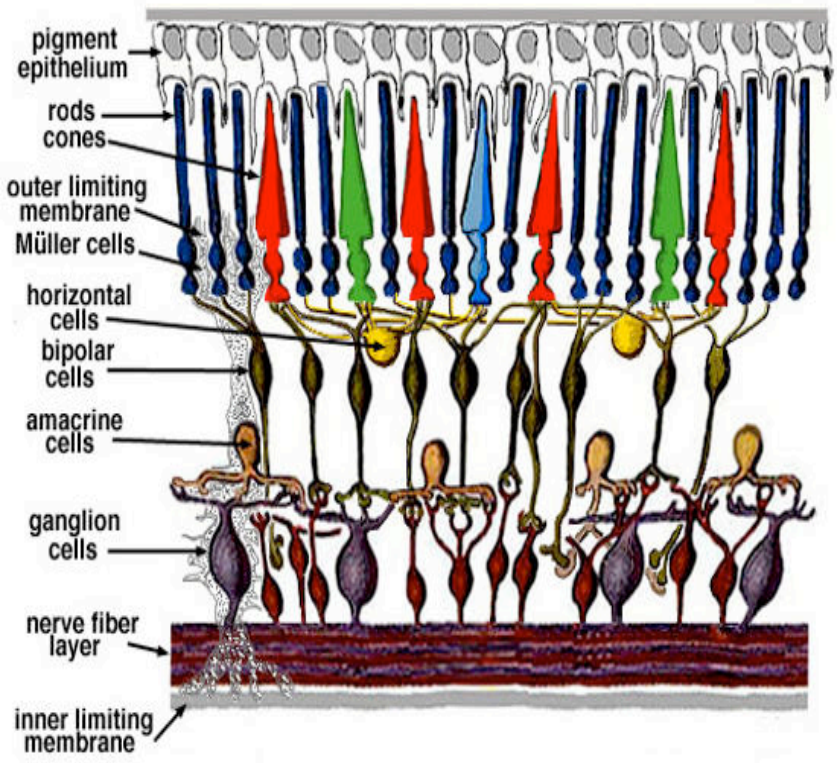
Introduction

The eye is a complex sensory organ which receives visual images and carries them to the brain. When a light stimulus is initiated, the light coming into the eye touches the three tunics, or layers, of the eye; the outer tunic, the middle tunic, and the inner tunic. The first tunic is the outer tunic (colored white in diagram above), which consists of the sclera and the cornea. This layer provides protection to the inner structures of the eye, and maintains the shape and consistency of the eyeball. The sclera is the part of the outer tunic that covers the back of the eye, while the transparent cornea, a clear dome, covers the front of the eye. (Szaflarski, D.M. 1999) The aqueous humor is a thin, watery fluid that fills the space between the cornea and the iris of the middle tunic. The middle tunic is also called the uvea (colored blue in diagram above), which reduces the reflection of light and contains blood vessels. The back of the uvea, located under the sclera, is called the choroid. The ciliary bodies of the uvea cause the iris to constrict or dilate to control the amount of light entering the pupil, the hole through which light enters the lens. After light moves through the lens, it enters the vitreous humor and then the inner tunic. The inner tunic is the retina (colored red in diagram above), the most important part of the eye in terms of sight. The retina is the part of the eye that receives light impulses and converts them into energy that can be passed on to the brain. (Montgomery, T., 1998) Therefore, to understand how a human being is able to see, one must look into the inner workings of the retina, the most vital part of the visual process. The purpose of this paper is to describe the functions of the different types of cells found in the retina, and how each contributes to sight.

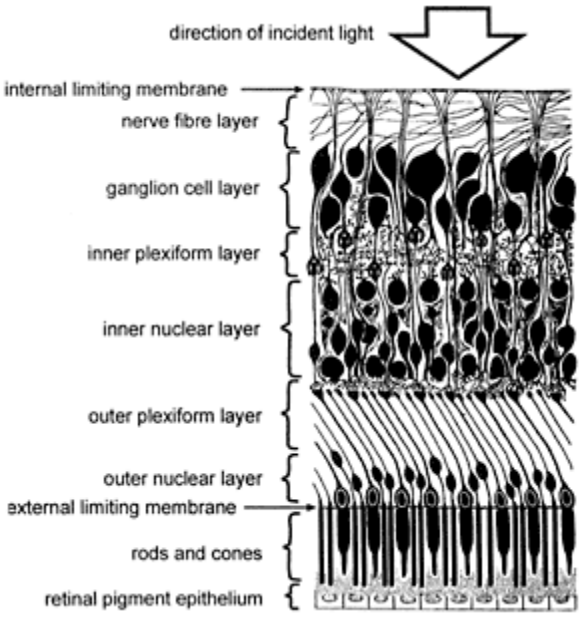
The retina has ten layers; the pigmented epithelium, the inner and outer segments of rods and cones, the outer limiting membrane, the outer nuclear layer, the outer plexiform layer, the inner nuclear layer, the inner plexiform layer, the ganglion cell layer, the nerve fiber layer, and inner limiting membrane. By following the nerve cells through these layers, one can see the pathway that the converted energy of light impulses takes to reach the optic nerve, which leads to the brain.

The pigmented epithelium is located on the external retinal wall, providing vitamin A, or retinal to the photoreceptors that it contacts. The layer of the rods and cones is where the conversion of light to energy takes place. The junctions between the rods and cones and the Müller cells make up the outer limiting membrane, which forms a blood retina barrier, isolating the inner layers of the retina from harmful substances in blood. The outer nuclear layer contains the nuclei of rods and cones. The outer plexiform layer is the layer in which the axons of the cones and rods synapse with the dendrites of the bipolar and the neurites of horizontal cells. The inner nuclear layer contains the nuclei of the bipolar, horizontal, and amacrine cells. In the inner plexiform layer, the axons of bipolar cells synapse with the neurites of amacrine cells and the dendrites of ganglion cells. In this layer, the neurites of amacrine cells also synapse with ganglion cell dendrites. The ganglion cell layer contains the nuclei of the ganglion cells, which then converge in the nerve fiber layer. The inner limiting membrane is made up of Müller cells, which form a barrier between the retinal nerve cells and the potentially harmful substances in the

vitreous humor. (Caceci T., 2001) Each type of cell in the pathway has its own functions which help to increase the accuracy and speed of vision.



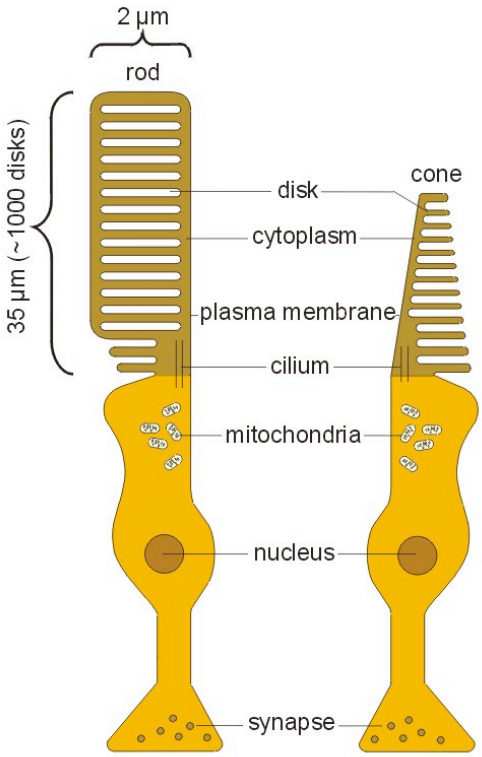
(Kolb H. et. al. 1996)



(Gurney P.W.V. 1999)

Rods and Cones

When light hits the retina, it first goes through all the layers of the retina before the cells begin to respond. This is because the photoreceptor cells, the rods and cones, are located on the outer region of the retina, furthest from the lens.

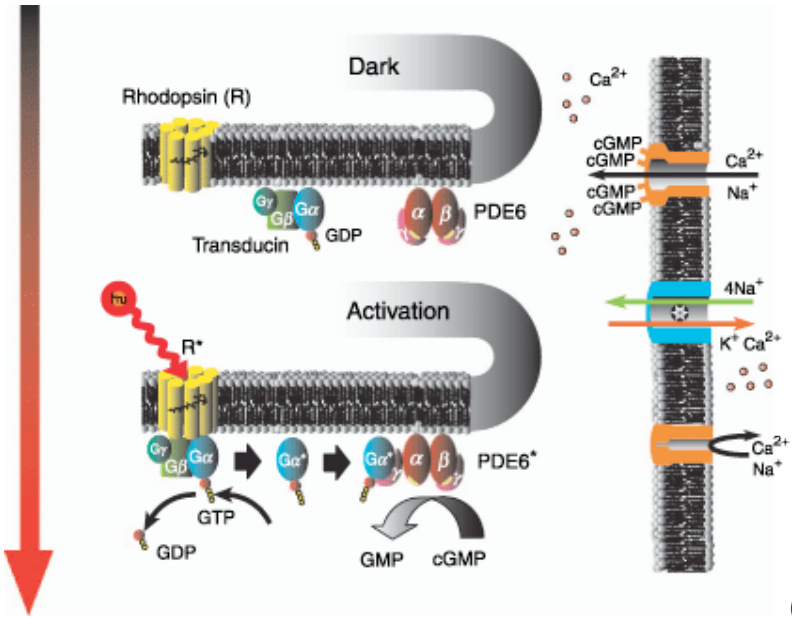


(Juelich F., 2004)

Both rods and cones are made up of two segments, the outer segment and the inner segment. The outer segment exhibits flat, membranous disks containing a photo pigment. The disks are infoldings of the plasma membrane that become narrower as they move away from the modified cilium, the connecting region between the inner and outer segments. These disks are produced in the inner segment and are transported by kinesins and cytoplasmic dyneins along microtubules toward the outer segment across the bridge of modified cilium. The disks are continuously being renewed; the used disks are phagocytosed by cells of pigmented epithelium. The inner segment is abundant in mitochondria; mitochondria are involved in the synthesis of adenosine triphosphate, the Golgi apparatus, and endoplasmic reticulum. (Caceci T., 2001)

Rods contain the pigment rhodopsin, which functions during night vision, while cones contain iodopsin, which helps to see more accurate detail and color. There are three types of cone cells, which respond to different regions of the spectrum, discriminating the colors blue, green, and red. There are other differences between the two cells. In the cone cell the outer segment is conical, while in the rod cell it is cylindrical. The cone cell axon ends in a cone pedicle, a large, conical, flat end, which is thicker than the rod spherule, small round enlargements of the axon. Both rod and cone synapse with the cytoplasmic processes of bipolar and horizontal cells. (Kolb H. et. al. 1996)

Rods and cones are transducers; they convert light into electrical or neural energy. In order for this to occur, the rods and cones need photopigments. The protein opsin and a chromophore, retinal, constitute the photopigments of the rods and cones. The chromophore is needed so that color will be absorbed; without the chromophore, the photoreceptor would just absorb UV light. The photopigments are needed to provide the energy required to cause an electrical change in the membrane of the rod or cone that will be propagated from the point of absorption of the light to the rod spherule. The electrical change occurs when the photoreceptor is bleached, the process in which the photopigment absorbs a photon and changes chemically into its constituents, which are less sensitive to light. In darkness, the rod and cone cells are depolarized, and they continuously release the neurotransmitter glutamate to the bipolar cell; this inhibition of the bipolar cell is known as the "dark current." As light hits the photopigment, retinal is activated. This causes the opsin to activate transducin, which activates phosphodiesterase. Phosphodiesterase breaks cyclic guanosine monophosphate down into guanosine monophosphate. The cell membrane becomes hyperpolarized, and glutamate is no longer released to the bipolar cell. This causes the bipolar and horizontal cells to hyperpolarize as well, and the message continues along the chain. (Stockman A. et. al. 2007)



(Stockman A. et. al. 2007)

Horizontal Cells

Horizontal cells are one of the intermediaries between photoreceptors and ganglion cells. Their nuclei are found in the inner nuclear layer, and their neurites, their cytoplasmic processes (they do not

have axons or dendrites), attach to the rod spherules, cone pedicles, the dendrites of bipolar cells, and the neurites of other horizontal cells in the outer plexiform layer. One horizontal cell synapses with more than one type of cell at the same time, because each neurite can have many branches. Because the horizontal cell has many branches and can reach many cells horizontally across the outer plexiform layer, it allows one part of the retina to influence the other part's activity. Horizontal processes are in close proximity to retinal capillaries, and there may be neurovascular coupling between the processes and the capillaries. Such intimate contact with the capillaries was previously thought to be a characteristic of Müller glial cells and astrocytes; some species of horizontal cells have glial proteins (glial fibrillary acidic protein or vimentin), and both horizontal cells and glial cells develop from the same precursors during retinal development. (Mojumder D.K. 2009)

The membrane of the horizontal cell contains ionotropic glutamate receptors which need direct activation by glutamate. The receptors are ionotropic because the receptor and the ion channel form one complex, so they directly gate ion channels; they open ion channels when receiving glutamate. Glutamate release from rods and cones causes glutamate to be received by the glutamate receptor, which then causes the cell to be depolarized; a decrease in glutamate, a response to light, causes hyperpolarization of the cell. The horizontal cells provide feedback control of photoreceptor synaptic output. They perform negative feedback to photoreceptor synaptic terminals at the first synapse of the visual pathway. The cell exerts a restraining influence on the junction by stopping the response from continuing to the bipolar cells. It is widely believed that these restraining influences only occur on cones, not rods. The role of horizontal cells on the rod pathway is unclear. (Bloomfield S.A. et al 2001)

The three different types of cones transmit their effects to bipolar and horizontal cells. In many experiments conducted on horizontal cells, the cells showed two types of potentials when recorded, color and luminosity. The color types of cell give an opponent type of response; the colors blue and yellow have opposing effects in some cells, while red and green have opposing effects in other cells. The blue-yellow cell has connections with blue and red and green cones, while the red-green cell has connections with only red and green cones. The transmission of different wavelengths to different types of horizontal cells leads to a detailed color-coded message that is passed on to the optic nerve. (Burkhart D.A. et. al., 1978)

Bipolar Cells

Bipolar cells, like horizontal cells, are intermediaries between photoreceptors and ganglion cells. Their nuclei are found in the inner nuclear layer, their dendrites contact photoreceptor cell terminals in the outer plexiform layer, and their axons stretch into the inner plexiform layer to contact ganglion cells. Bipolar cells can be subdivided based on the photoreceptor cells they synapse with. Therefore, there are rod bipolar cells, which synapse with rod spherules only, and there are cone bipolar cells, which synapse with cone pedicles only. The cone bipolar cells can be further divided into the midget cone bipolar cell and the diffuse cone bipolar cell. The midget bipolar cell synapses with a single cone cell, and has only one axon which contacts a single ganglion cell, which is continuous with the optic nerve. In reality, a true

one to one connection in the retina does not exist, because although one midget bipolar cell can contact one cone pedicle, a diffuse bipolar cell can attach to the same cone as well. Also, horizontal and amacrine cells contact midget bipolar cell, ganglion cells, and cones laterally. Because of the interconnections between the nerve cells, no optic nerve fiber actually carries messages from one cone, but because of the midget bipolar cell pathway, an increased level of acuity is reached when a less dilute message reaches the optic nerve. It is this pathway that causes cone vision to be more accurate than rod vision. The diffuse cone bipolar cell contacts up to seven cone cells at one time and synapses with many ganglion at a time. The diffuse cone bipolar cell has wider input and output pathways than the midget bipolar cell. (Kolb H. et. al. 1996) Cone bipolar cells can also be divided into invaginating cone bipolar cells, whose dendrites penetrate the synaptic invaginations of the cone pedicles, and flat cone bipolar cells, whose dendrites remain superficial and establish basal contacts. (Bloomfield S.A. et al 2001)

One rod bipolar cell can synapse with up to fifty rods. This causes the same effect if there are one hundred quanta falling on a single rod or one quanta falling on one hundred rods. There is no difference, because ultimately the same signal will reach the bipolar cell. Also, if a high density of rods converges on a single bipolar cell, and a high density of bipolar cells converges on one ganglion cell, there are many signals falling on one ganglion cell. During night vision, the power of bipolar and ganglion cells to collect impulses increases; the impulses were previously inhibited by higher illumination of the retina. This causes an increase in the amount of signals on the ganglion cell; it is because of this large amount of converging that during night vision, visual acuity is decreased. With so many impulses entering the ganglion cell, the cell can not interpret all the impulses to the degree where vision would be as accurate as it is during normal vision. (Kolb H. et. al. 1996)

When there is a decrease in glutamate levels as a response to light, the photoreceptor cells depolarize, which causes the bipolar cell to depolarize or hyperpolarize depending on whether the cell is an ON-bipolar cell or an OFF-bipolar cell. With decreased glutamate, an ON-bipolar cell depolarizes and an OFF-bipolar cell hyperpolarizes. In the rod vision pathway, rod bipolar cells contact two types of amacrine cells, which serve as interneurons in the transmission of light signals in night vision. These amacrine cells, AII amacrine cells, then transmit the signal to cone bipolar cells, the final conduit to the ganglion cell during rod vision. Cone bipolar cells are used during rod vision, revealing that the rod and cone circuits are intertwined. (Bloomfield S.A. et al 2001)

Amacrine Cells

Amacrine cells are interneurons with nuclei in the inner nuclear layer. They have one neuritic process which branches and connects to the axons of the bipolar cells and the dendrites of the ganglion cells in the inner plexiform layer. Like horizontal cells, amacrine cells connect to bipolar and ganglion cells horizontally, so that one area of the retina can impact another area. All amacrine cells display dendritic and somatic impulse activity. This impulse activity is important, as it performs feedforward inhibition on ganglion cells and feedback inhibition on bipolar cells via action potentials. The amacrine cell exerts a restraining influence on certain junctions of the retina, reducing the spread of messages. In

relation to the ganglion dendritic tree, bipolar cells make up the center of the receptive field, while amacrine cells make up the periphery. When the amacrine cells exert an inhibitory action, the bipolar cells in the central zone of the field are prevented from responding to the receptors, and the message is not sent to the ganglion cell. (Kolb H. 2003) The inhibition caused by the amacrine cell has two distinct modes, local and global. If the action potential can not be propagated down the cell to the dendrites then they provide local inhibition. If, however, the action potential invades the entire dendritic tree, it provides global inhibition. Amacrine cells can be divided into different types based on the size of their dendritic spread, dendritic sublamination patterns, neurotransmitter subtypes, and variations in the morphological features. (Royer A.S. et al 2007) There are three specific types of amacrine cells discussed in this paper; A1 amacrine cells, indoleamine-accumulating cells (IAC), and AII amacrine cells.

The A1 amacrine cell is a spiking, axon-bearing interneuron in the retina, with thick, spiny, and highly branched dendrites in the inner plexiform layer. A1 cells receive inputs to their dendrites that cause depolarization, which initiates an action potential. The action potential then propagates down the axon and crosses the retina. The A1 cells have extensive branching, indicating that they serve a global function in vision processing. A1 cells are mediators of long-range inhibition of ganglion cells in response to global image motion. Their spiking output structures may be a key element in long range lateral inhibition of the retina. The A1 cells have center-surround receptive fields which combine inputs from ON bipolar cells and OFF surrounds and OFF bipolar cells and ON surrounds. Because amacrine cells are stimulated by both ON-center and OFF-surround, and OFF-center and ON-surround, the inhibition of amacrine cells is postsynaptic to all bipolar cells, regardless of their responses to stimulation. A1 amacrine cells provide inhibitory feedback on all bipolar cells. (Davenport C.M et al 2007)

IAC amacrine cells, also known as A17 amacrine cells, account for half of the rod bipolar cell output. IAC cells receive input from rod bipolar cells and multiple types of amacrine cells in the inner plexiform layer. The sole postsynaptic target of IAC cells is rod bipolar cells; IAC cells return reciprocal synapse back onto rod bipolar cells. This arrangement causes an interconnecting of rod bipolar cells in the inner plexiform layer. IAC amacrine cells contain GABA, and there are GABA receptors present on the axons of the rod bipolar cells; this indicates that the IAC cell has an inhibitory feedback function in the reciprocal synapse. (Bloomfield S.A. et al 2001)

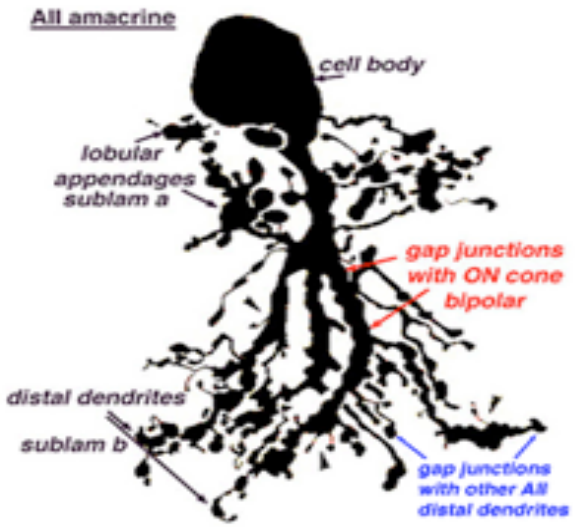


Fig. 11. A Golgi stained example of an AII amacrine cell in cat retina.

(Kolb H. et. al. 1996)

AII amacrine cells function during rod and cone vision. In scotopic vision, night or dim-lit vision, AII cells are major carriers of rod signals to ganglion cells. They receive input from rod bipolar cells, but do not return the signal back to rod bipolar cells. Instead, the cells form homogenous gap junctions with other AII cells near the site of the synapse of the rod bipolar cell. The AII cells then synapse with the axon terminals of cone bipolar cells. AII cells also receive input from cone bipolar cells, indicating that the cells are also part of the photopic, normal light vision. AII amacrine cells are in dense population in most of the retina because they are a key element in the visual process. (Bloomfield S.A. et al 2001)

Ganglion Cells

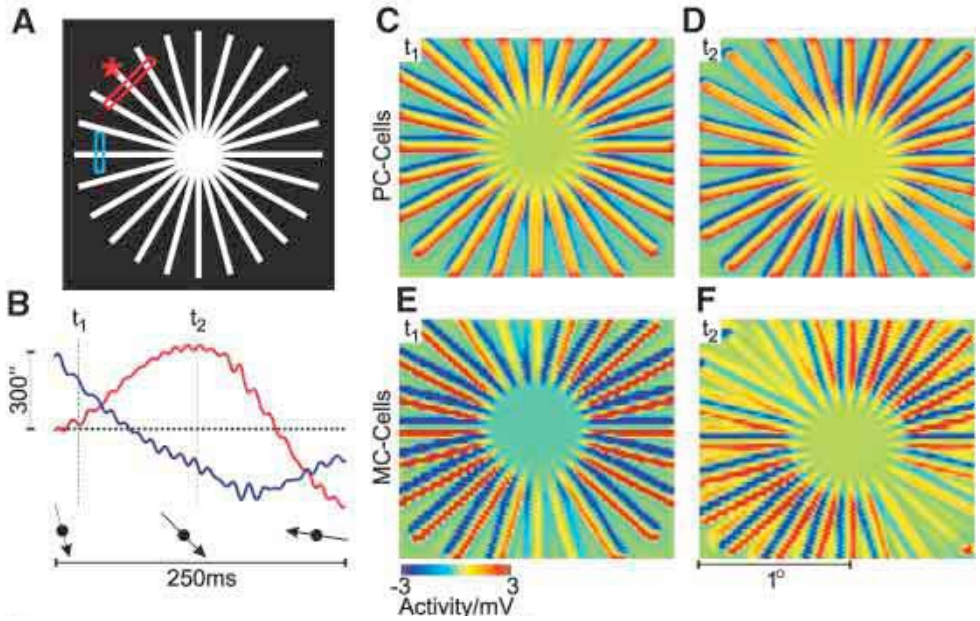
Ganglion cells are the last retinal cells in the visual pathway; their axons form part of the optic nerve. The nuclei of the ganglion cells are in the ganglion cell layer, and their dendrites extend into the inner plexiform layer and synapse with bipolar cells. There are two types of ganglion cells; midget ganglion cells, which synapse with only one bipolar cell, and diffuse ganglion cells, which synapse with several bipolar cells. The midget ganglion cells receive impulses from midget cone bipolar cells, so they are part of the cone visual pathway only. (Kolb H. et. al. 1996) The ganglion cell receives information from all stages in the visual pathway. The ganglion cell can convey signals that drive the circadian and pupillomotor systems by combining the rod and cone photoresponses, as well as its own photoresponses. (Dacey D. M. et al 2005)

The ganglion cell response is not switched on and off as the light source is switched on or off. When the light source is emitting light to the central zone of the receptive field, a discharge is produced. The periphery zone of the receptive field has the opposing response, and will only produce discharge if there is no light. The center and the periphery usually have opposite responses in terms of color; for

example, an off-response to green in the surrounding area and an on-response to red in the center of the field. A simultaneous stimulation of red in the center and green in the periphery would elicit no response, because the on-response of the center is cancelled out by the off-response of the periphery. This opponent organization serves to enable the retina to emphasize different colors; the involuntary movements of the eye in normal vision keeps shifting the boundaries of the center and the periphery, causing different colors to be seen. Another effect of this inhibitory organization is to prevent unneeded information from reaching the brain. There are about one million optic nerve fibers, and if all of them were discharging information at once, the brain would have too many messages to decode. This mechanism helps to cut down the amount of information the brain needs to process. (*Encyclopædia Britannica* 2009) Another method that some ganglion cells use to decrease the amount of action potentials it sends to the optic nerve is to respond to light moving only in a specific direction. When an object moves in the ganglion's preferred direction an excitatory impulse occurs. When the object moves in the opposite direction, however, both excitatory and inhibitory impulses occur, effectively canceling each other out. (Barinaga M. 2000)

Each ganglion cell carries a chemical tag that corresponds to chemicals in the tectum, the dorsal part of the midbrain; these chemicals convey positional information to the cell. The ganglion cell interprets this information and responds by connecting to a specific point in the brain. There are two gradients in the ganglion cell pathway to help the axons of the ganglion cells hit their target position exactly. The gradient made up of molecules in the tectum called EphrinA specifies where the ganglion axons will end up in terms of the anterior-posterior axis. The gradient made up of molecules called EphrinB specifies where along the medial-lateral axis the axon will end up. If an axon is moving in a direction that is either medial or lateral to its destination, it projects branches towards the destination. The EphrinB regulates this branching. The Wnt3 protein counteracts the pull of EphrinB towards the most medial tectum, so the lateral tectum is not empty. The gradient of Wnt3 is along the same direction as EphrinB's gradient, but is a repellent gradient. Ryk, the receptor for Wnt3 on the ganglion on cell, is expressed in ganglion cells in the same direction as EphrinB, proving that it is Wnt3 that provides the repellent gradient. (Liqun Luo 2006)

A specific type of ganglion cell, the magnocellular (MC) ganglion cell, was experimented on and found to be responsible for the visual illusions that are seen during fixational eye movements. When one stares at a stimulus, such a star or an optical illusion, for a period of time, there is an apparent splitting of the lines, as well as a fading of lines or whole wedges of the stimulus. These characteristics are not found in parvocellular (PC) ganglion cells, the other type of ganglion cell. This indicates that MC cells dominate during fixational eye movements, as their properties are such that this would happen. In the diagram below, it is shown that in fixational eye movements, such as staring at the star shaped stimulus (A), MC cells exhibit more line fading and splitting than PC cells. (Hennig M.H. et al 2007)



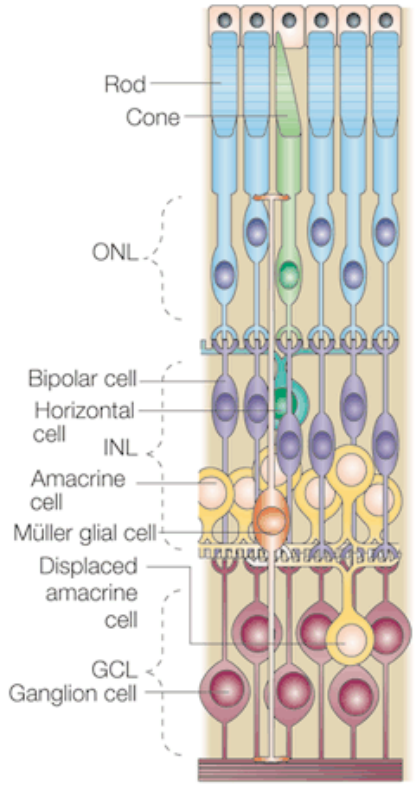
(Hennig M.H. et al, 2007)

Intrinsically photosensitive retinal ganglion cells (ipRGCs), or melanopsin-positive ganglion cells, are ganglion cells that function as a circadian photoreceptor. Mice with severe degeneration of rods and cones, or with no rods and cones at all, still follow circadian rhythms based on light. Light affects a circadian phase by activating the retinohypothalamic tract, which connects ipRGCs to the superchiasmatic nucleus, a part of the hypothalamus. The ipRGCs are the only ganglion cells found to contain melanopsin, an opsin which is photosensitive, indicating that this is the part of the ipRGC that makes it a photoreceptor. IpRGCs are different than the classical photoreceptors in that they depolarize when stimulated by light, while rods and cones hyperpolarize. IpRGCs are also less sensitive and more sluggish than the classic photoreceptors. The melanopsin-positive ganglion cells contribute to light-stimulated effects on sleep, heart rate, cortisol levels, alertness and other effects of the circadian cycle. The pupillary light reflex, where light causes the size of the pupil to decrease and darkness causes the pupil to dilate, is controlled by ipRGCs as well. The cells also perform the normal function of ganglion cells, receiving synaptic input from bipolar and amacrine cells. (Berson D. M. 2003)

Müller Cells

Müller cells, a specific type of glial cell, fill the spaces between the photoreceptors, bipolar cells, ganglion cells, and other cells in the visual pathway. Müller cells are not part of the visual pathway; they do not synapse with any cells, and they do not receive or send signals. Their function is mainly to support and regulate the retina. The nuclei of Müller cells are found in the inner nuclear layer, and their cytoplasmic processes extend to the outer and the inner limiting membranes. The inner limiting membrane, which separates the retina from the vitreous body, is made up of the basal lamina of Müller cells. The outer limiting membrane is located at the contact site where zonula adherens and

microvilli extending from Müller cells connect the photoreceptors with the glial Müller cells. (Kierszenbaum A.L. 2007)

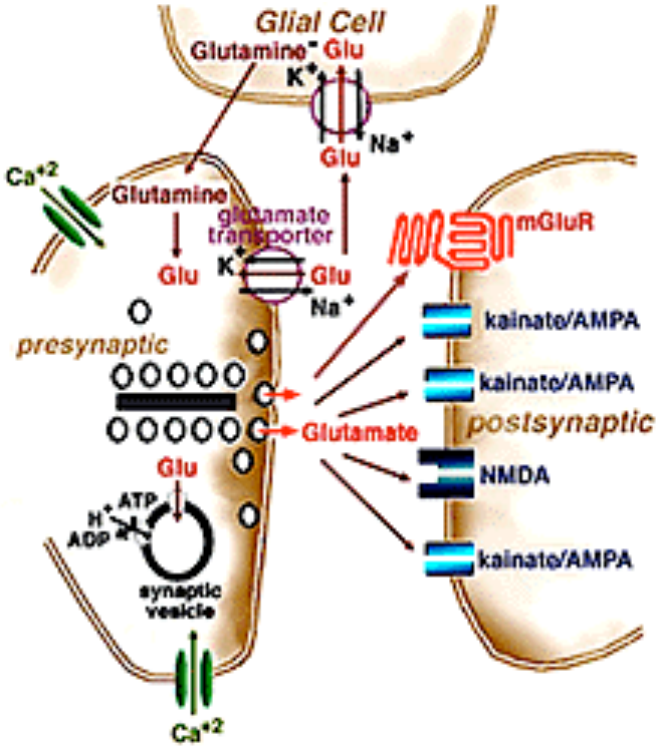


Nature Reviews | Neu(Dyer, M.A. et. al., 2001)

Before reaching the photoreceptors, light has to go through each layer of the retina. At each layer, the light is refracted by the cells in that layer, ultimately causing less light to fall on the photoreceptors. The Müller cells have a higher refractive index than the other cells, which means that light can be channeled through the cells with little loss, so most of the light hitting the retina is received by the photoreceptors. This high refractive index is caused by the tight bundles of polymer fibers that extend along their lengths. (Castelvecchi, D. 2007)

Müller cells have many different functions in the retina. They regulate extracellular space, and ion and water levels. They maintain the blood-retinal barrier, and retinal blood flow. They provide trophic substances to the nerve cells, and they remove neural waste, such as carbon dioxide and ammonia. (Kolb H. et al 1996) They also modulate neuronal excitability and transmission by sending gliotransmitters to the neurons. They also supply the end product of anaerobic metabolism, they break down glycogen, so that the nerve cells in the retina can perform aerobic metabolism. Müller cells and astrocytes, another type of glial cell found in the retina, remove glutamate, an excitatory neurotransmitter, and gamma-Aminobutyric acid (GABA), an inhibitory neurotransmitter from the extracellular sites in the retina. Müller cells take up glutamate by utilizing glutamate transporters like GLAST, glutamate-aspartate transporter, and convert it into glutamine with the enzyme glutamine

synthetase. If the glutamate transporter is malfunctioning, the extracellular glutamate levels rise to excitotoxic levels, causing damage to the retina. Müller cells uptake GABA using GABA transporters (GATs), and convert it to glutamate using GABA transaminase. (Bringmann A. et. al. 2009)



(Kolb H. et. al. 1996)

The *fovea centralis* is a unique portion of the retina where an abundance of light is absorbed and as such contains no rods; only cones. These Müller cells provide the primary structural support for the fovea centralis, binding the photoreceptor cells together. The cells are also a reservoir for retinal xanthophyll, yellow accessory pigment, which is partly responsible for the low density of the cell cytoplasm in the fovea. Müller cells in the *fovea centralis* also have a primary role in age related macular hole formation, providing an anatomical substrate for schisis to occur. X-linked juvenile retinoschisis, the abnormal splitting of the retina's neurosensory layers, is thought to be caused by degeneration of the inner portion of the Müller cells in the *fovea centralis*. (Gass J.D.M. 1999)

In addition to Müller cells and astrocytes, there are also other glial cells found in the retina. Microglial cells are blood-derived immune cells which reside in the retina. They play important roles in host defense against invading microorganisms and the initiation of inflammatory processes and tissue repair. They are present in all layers of the retina. (Bringmann A. et. al. 2009)

Conclusion

At first glance, the reason for the retina's interbranching visual pathway is hard to understand. But, after putting together the functions of each type of retinal nerve cell, one sees that each cell is

essential. The complexity of the pathway serves to clarify the messages coming into the eye, and to prevent unnecessary information from being transmitted to the brain. Understanding how the retina functions is important for doctors and scientists who are diagnosing and treating patients who have nerve damage in the retina. Knowing the function of each area and cell type in the retina can help to diagnose what area is damaged when seeing certain symptoms present, and treatment can then be administered. We know that Müller cells in the *fovea centralis* have roles in X-linked juvenile retinoschisis and age related macular hole formation. Further research is being done by foundations such as the Retina Research Foundation in Houston, Texas, in order to further understand the function of each nerve cell in the eye and how each cell can lead to ocular disease.

The intricacy of the eye, and especially the retina, which is such a small part of our body, is awe-inspiring. It is amazing to learn the workings of vision, something that is done almost every waking second, and to actually understand what is happening each moment in one's eye.

References

Barinaga, Marcia. (2000) "How the Retina Does the Math." *Science Now*: 2. *Academic Search Complete*, EBSCO*host*. http://web.ebscohost.com.lb-proxy8.touro.edu/ehost/detail?vid=4&hid=108&sid=929b190f-4b36-4d16-aef9-d9a474538413%40sessionmgr103&bdata=JnNpdGU9ZWhvc3QtbGl2ZQ%3d%3d#db=ulh&AN=3610379

Berson D. M. (December 2003) "Strange vision: Ganglion cells as circadian photoreceptors." *American Journal of Ophthalmology*, Volume 136, Issue 6, Page 1199. Sciencedirect. http://www.sciencedirect.com/science/article/B6VK5-4B3DW4K-27/2/92535c610154d0f63d55e8ec9cfec2cd

Bloomfield S.A., Dacheux R.F. (2001) "Rod vision: Pathways and processing in the mammalian retina." *Progress in Retinal and Eye Research*. 20 (3), pp. 351-384. Sciencedirect.http://www.sciencedirect.com/science/article/B6TBT-42NRC21-4/2/7e4c83df126c3432811bf489654e83b6

Bringmann A., Pannicke T., Biedermann B., Francke B., Iandiev I., Grosche J., Wiedemann P., Albrecht J., Reichenbach A. (2009) "Role of retinal glial cells in neurotransmitter uptake and metabolism." *Neurochemistry International*, Volume 54, Issues 3-4, Pages 143-160. Sciencedirect. http://www.sciencedirect.com/science/article/B6T0B-4V3SY2J-4/2/da11636f50af2b6d6cf38bfa178d89c0

Burkhart D.A., Hassin G. (1978) "Influences of cones upon chromatic- and luminosity-type horizontal cells in pikeperch retinas." J Physiol. 281: 125–137. Pubmed. http://www.pubmedcentral.nih.gov/pagerender.fcgi?artid=1282687&pageindex=2#page

Caceci, T. (2001) “Anatomy and Physiology of the Eye.” Virginia/Maryland Regional College of Veterinary Medicine. http://education.vetmed.vt.edu/curriculum/VM8054/EYE/EYEDEMO.HTM

Castelvecchi, D. (2007) "Broadband vision." *Science News* 171, no. 0: 317. EBSCO*host.* http://search.ebscohost.com.lb-proxy8.touro.edu/login.aspx?direct=true&db=ulh&AN=25149423&site=ehost-live>.

Matthews, G.G. (2008) “Sensory Physiology.” Neurobiology. http://www.colorado.edu/intphys/Class/IPHY3430-200/008sensory.htm

Dacey, D. M., Liao, H.-W., Peterson, B. B., Gamlin, P. D., Robinson, F. R., Smith, V. C., Pokorny, J., & Yau, K.-W. (17 February 2005). “Melanopsin-expressing ganglion cells in primate retina project to the LGN and signal both color and irradiance.” *Nature* 433, 749-754. Proquest. http://proquest.umi.com.lb-proxy8.touro.edu/pqdweb?did=797582331&Fmt=6&clientId=14844&RQT=309&VName=PQD

Davenport C.M, Detwiler P.B, Dacey D.M. (2007). “Functional polarity of dendrites and axons of primate A1 amacrine cells.” *Visual Neuroscience,* **24**, 449-457. Proquest. http://proquest.umi.com.lb-proxy8.touro.edu/pqdweb?did=1457148581&Fmt=6&clientId=14844&RQT=309&VName=PQD

Dyer, M.A, Cepko, C.L. (2001) “Regulating Proliferation During Retinal Development.” *Nature Reviews Neuroscience* **2**, 333-342. Nature Reviews. www.nature.com/nrn/journal/v2/n5/box/nrn0501_333a_BX1.html

Eye, human. (2009) In *Encyclopædia Britannica.* Retrieved May 17, 2009, from Encyclopædia Britannica Online: http://search.eb.com/eb/article-64863

Gass, J.D.M. (1999) “**Müller Cell Cone, an Overlooked Part of the Anatomy of the Fovea Centralis: Hypotheses Concerning Its Role in the Pathogenesis of Macular Hole and Foveomacular Retinoschisis**.” *Arch Ophthalmol*, Jun 1999; 117: 821 - 823. Archives of Ophthalmology. http://archopht.ama-assn.org.lb-proxy8.touro.edu/cgi/reprint/117/6/821

Gurney, P. W. V. (1999) “Is our ‘inverted’ retina really ‘bad design’?” *Technical Journal* 13(1):37–44. Answersingenesis.org. http://www.answersingenesis.org/tj/v13/i1/retina.asp

Hennig M.H., Wörgötter F. (2007) “Effects of Fixational Eye Movements on Retinal Ganglion Cell Responses: A Modelling Study.” *Frontiers in Computational Neuroscience,* 1, 2. Pubmed. http://www.pubmedcentral.nih.gov/picrender.fcgi?artid=2525939&blobtype=pdf

Juelich F. (2004) “Photoreception.” *Institute of Structural Biology and Biophysics.* http://www.fz-juelich.de/isb/isb-1/Photoreception

Kierszenbaum A. L., (2007) *Histology and Cell Biology. An Introduction to Pathology*, 2nd ed. Philadelphia: Mosby/Elsevier. 251-272.

Kolb H., Fernandez E., Nelson R. (1996) “WEBVISION: The Organization of the Retina and the Visual System.” Webvision. http://webvision.med.utah.edu/index.html

Liqun Luo. (2006). "Developmental neuroscience: Two gradients are better than one." Nature. 439(7072), 23-4. Proquest. http://proquest.umi.com.lb-proxy8.touro.edu/pqdweb?did=967854121&sid=1&Fmt=6&clientId=14844&RQT=309&VName=PQD

Montgomery, T. (1998) "Anatomy Physiology and Pathology of the Human Eye." Anatomy of an Eye. http://www.tedmontgomery.com/the_eye/index.html

Mojumder, D.K. (2008) "Capillary-contacting horizontal cells in the rodent retina." *J Anat Soc India*. 57(1): 34–36. Pubmed. http://www.pubmedcentral.nih.gov/picrender.fcgi?artid=2613306&blobtype=pdf

Royer A.S., Miller R.F. (2007). "Dendritic impulse collisions and shifting sites of action potential initiation contract and extend the receptive field of an amacrine cell." Visual Neuroscience, 24(4), 619-34. Proquest. http://www.touro.edu.lb-proxy8.touro.edu/library/commerdb/proxyTC.asp?http://proquest.umi.com.lb-proxy8.touro.edu/pqdweb?did=1457148721&sid=1&Fmt=6&clientId=14844&RQT=309&VName=PQD

Stockman A., Smithson, H. E., Michaelides, M., Moore, A. T., Webster, A. R., & Sharpe, L. T. (2007) "Residual cone vision without α-transducin." *Journal of Vision*, *7*(4):8, 1-13, http://journalofvision.org/7/4/8/

Szaflarski D.M. (1999) "How We See: The First Steps of Human Vision." Access Excellence Classic Collection. The National Health Museum. http://www.accessexcellence.org/AE/AEC/CC/vision_background.php