The Human Eye

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1 Abstract

The eyes provide a profound part of the human experience. Not only do they allow us a sense of the world around us that empowers our survival, they also shape our very comprehension of the universe. Terms like "Vision" and "Foresight" are as often used in a philosophical context as in the context of physical sensation. Since vision is such a ubiquitous analogy, there is a great deal to be gained in sharpening one's understanding of the physical mechanism not only for scientific endeavors, but also to enrich the concept that permeates descriptions of the human experience at every level. This report is simply an overview of some of the concepts and facts that I have discovered in my research. The eye is a biological system and, as such, does not lend itself to simplification. What I have found is not a crisp analytical model, but a new sense of the complexity and power of our sense of vision.

"It's not what you look at that matters, it's what you see." - Henry David Thoreau

2 Introduction

Upon researching the human eye I have found it to be an exquisitely engineered piece of equipment. At a first glance it appears to be a sort of simple camera like optical system, with a two basic lenses, a diaphragm, and a photosensitive surfaces on the back. One simply shines light in and gets an image on the retina, which is a projection screen that the person inside the head gets to watch. With just a little deeper investigation, though, one is overwhelmed by the complexity and apparent 'cleverness' of its various systems, from the maintenance tools that constantly repair damaged parts to the surprising capacity for the brain to maximize its use of this phenomenal sensor. Attention could be paid to any number of the detailed workings of the eye, but I intend to narrow my discussion to the optical path of the eye as much as possible, and finally to discuss the translation of light into an image on the mind. I will begin with an overview of the basic elements that light interacts with in passing from the outside world into the retina.

Cornea The cornea (Latin - "Horn") provides the primary refractive interface of the human eye. This becomes obvious when one discovers the refractive indexes of the various elements in the optical path. Because the internal elements have indexes ranging between about $n = 1.3$ and $n = 1.4$, the interface between the air ($n_a \approx 1.0$) [4, page 56] and the Cornea ($n_c \approx 1.376$) [4, page 178-179] have a much greater ratio than any other interface and therefore, by Snell's law, tends to bend the light more.

Though the cornea has a fixed shape so that its focal point cannot be adjusted, it has a specialized geometry that reduces spherical aberration. Near the center both the anterior and posterior surfaces have an approximately spherical shape, but as the surfaces sweep out from the center they become 'flattened out' attaining a more parabolic shape near to the edges. In addition to providing some aberration correction, this allows for a smooth transition to the larger radius of the sclera (The white of the eye). [2, page 15]

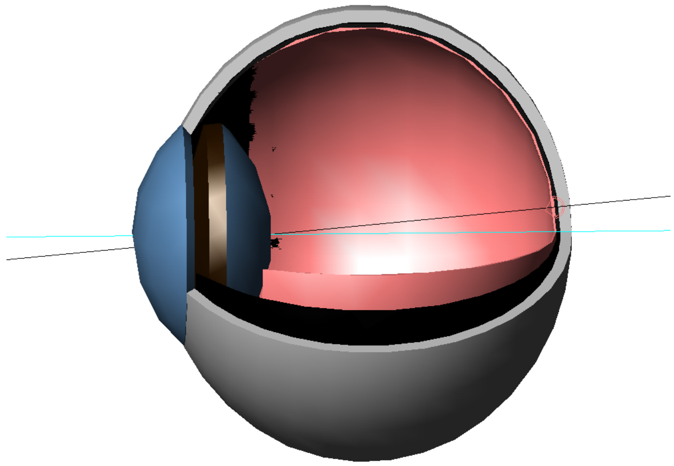

Figure 1: Partial section of eyeball, scale drawing.

Aqueous Humor Behind the Cornea is a clear fluid called the aqueous humor (Latin - "Watery Fluid"). This fluid is maintained at a pressure slightly higher than that of the atmosphere which keeps the Cornea 'pushed out' in its spherical shape that protrudes slightly from the main globe of the eye. Its index of refraction ($n_{ah} \approx 1.336$) [4, pg 178] is slightly below that of the cornea so that it causes the light to bend just slightly away from the optical axis.

Iris Acting as the aperture stop for the eye is the iris (Greek - "Rainbow"). It is a pigmented diaphragm that can expand or contract by the tensing and relaxing of muscles contained within it. The pupil (Latin "doll") is the opening through it's center. The Iris is a very dynamic mechanism that can contract to make the pupil as small as 1.5mm and relax to open as wide as 8 or 9mm [1]. This affects the amount of light entering the eyeball and therefor incident on the retina and also affects the depth of field.

Lens The lens (Latin - "Lentil [been]") is an extremely sophisticated element of the eye. Sitting three or four centimeters behind the Cornea, it provides the ability to adjust the focal point of the eye to create sharp images of objects near and far. To achieve this it flexes to adjust the radii of the anterior and posterior surfaces. In addition to being adjustable, the Lens can be characterized as a gradient index (GRIN) system. [4, page 136] Made up of about 22,000 layers [4, page 178] the index of refraction varies from about 1.406 near the center to 1.386 at the outer layers. This has many implications about how the optical path can be specifically 'conditioned' at different distances from the optical axis. These will be discussed further in section 3.

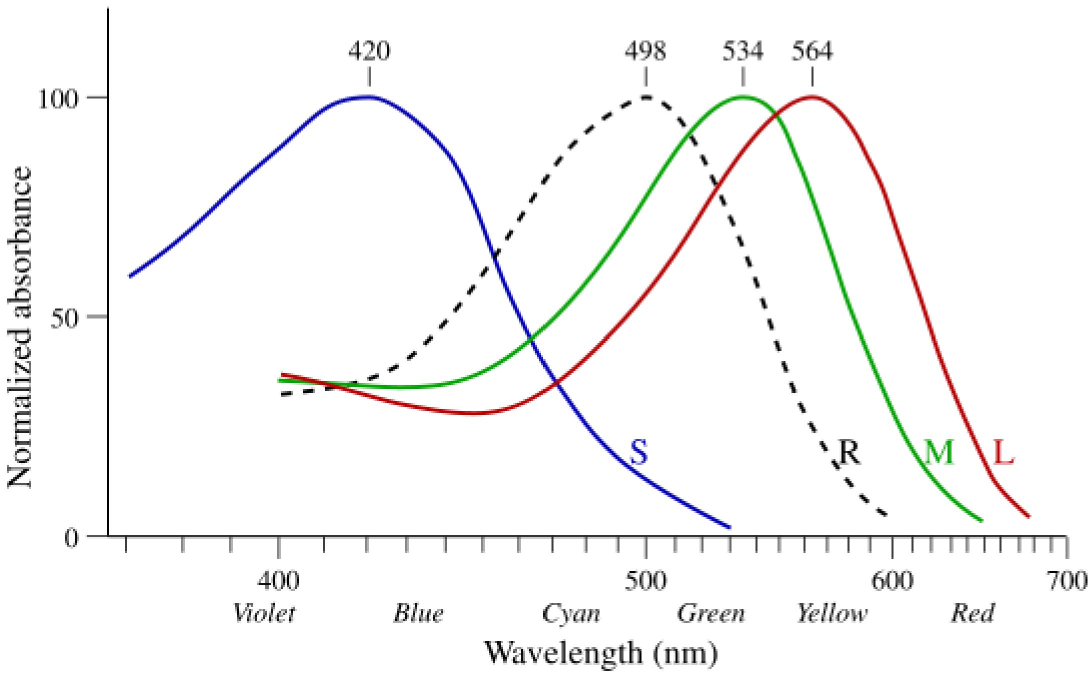

Figure 2: Retinal Sensitivity Spectrum

Vitreous Humor Filling the majority of the volume of the eyeball is the vitreous humor (Latin - "Glassy Fluid"). It is a very gelatinous fluid that is more or less stationary in the eye (In other words it doesn't flow about in the eye like a fluid would). When an item such as a blood cell gets 'stuck' in the vitreous humor it can stay suspended there indefinitely and occasional blocks a little bit of light to the retina producing what appears to be a 'floater' in the eyeball. The index of refraction of the Vitreous Humor is just slightly above that of the aqueous humor with $n \approx 1.337$ which provides the final interface for refraction between the posterior of the lens and the retina.

Retina The retina (Latin - "Net") is the term used for an extensive system of photosensitive cells on the interior surface of the eyeball that change the optical images into signals that are sent into the brain. They consist of three diverse regions with various concentrations of cells called rods and cones. The center and densest region of the retina is called the fovea (Latin - "Pit"). It contains only cone cells. The line passing from the center of the iris to the fovea is called the visual axis because it is the axis that both eyes align at the center of focus (Latin - "Fireplace"). The macula lutea (Latin - "Yellow Spot") surrounds the fovea and is an area about 5mm in diameter with very dense photocells, mostly made up of cones. Outside of this region cones grow less dense and finally even the rods become sparse. This is where peripheral vision takes place. Because of the lack of cones it is not sensitive to color and with increased distance from the fovea it is less sensitive to shape and finally becomes sensitive only to flashes of light. [1]

Trichromatic vision is achieved by the cones. A simple understanding of the sensation of color can be achieved by imagining the power absorbed by the eye as a vector with three coordinates, one for each pigment. The color is determined by the relative weights of the three components and the intensity is determined by the magnitude. This is not a one to one mapping from the visible light spectrum to the 'color' sensed. For example, "yellow" light may be obtained by shining a weighted mixture of red and green wavelengths of light into the eye, or by shining a single wavelength from the 'yellow' part of the visible spectrum. Thus, a computer monitor does not require all of the wavelengths of the rainbow to achieve all of the colors of the rainbow. These three pigments have been carefully measured and determined to have spectral response shown in figure 2. [3]

3 Content

There are two technical aspects of the eye that I would like to consider in this report. The first is a discussion of the lens which I found very fascinating. There is very little that I could do experimentally with the lens, so I primarily used analytical experiments in an attempt to uncover some of its subtle capacities. The second aspect that I considered was intended to be a simple experimental analysis of the peripheral vision. Though my experiments began simply enough, I quickly ran into trouble and discovered that the question of "What is the range of angles that the eye can see?" is not so easily answered.

The Lens As indicated in section 2, the lens is much more specialized that anything one might find in a camera. Particularly astonishing is the fact that it does not have a single index of refraction that one finds in homogenous lenses, but a whole gradient of refraction indices due to thousands of layers of proteins. The effects of this layering are not fully understood, but by taking a naive viewpoint I have uncovered two possible 'inspirations' for this property.

The first and most obvious reason for having a gradient of indices is to allow for a thinner lens. The reason for a thick section in the center of a homogenous lens and thinner part at the outside edges is to "slow down" the light (To the same speed) for different distances thereby achieving equivalent optical path lengths. There is a second option, however, if the lens is allowed to have different indices of refraction depending on the part of the lens. In the case where the center has a higher index of refraction the light can be slowed down to a slower speed than the outside of the lens, thereby making an equivalent optical path length without requiring as much distance of material to travel through. This is, indeed, the situation with the lens of the eye.

A second reason is to allow the lens to correct for spherical aberrations. Using a CAD program, a simple model of a 'layered' lens was created in order to investigate the possible effects. Figure 3 shows a ray diagram for a scale model with a simple spherical lens. Apparently the focal point is not exactly on the back of the eye. This is simply because eyes very from person to person and must have the ability to grow into a working shape even though

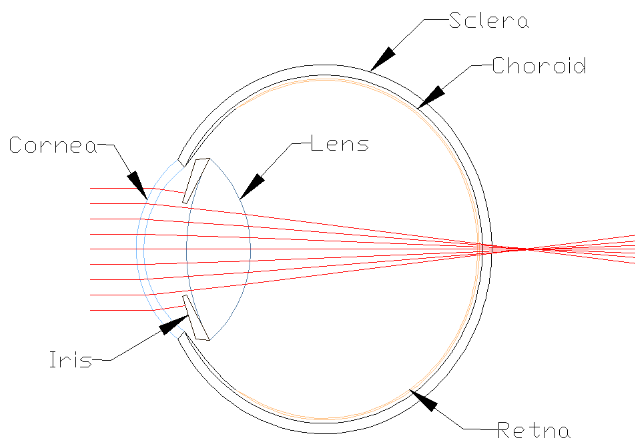

Figure 3: Solid Lens, $n_s \approx 1.391$

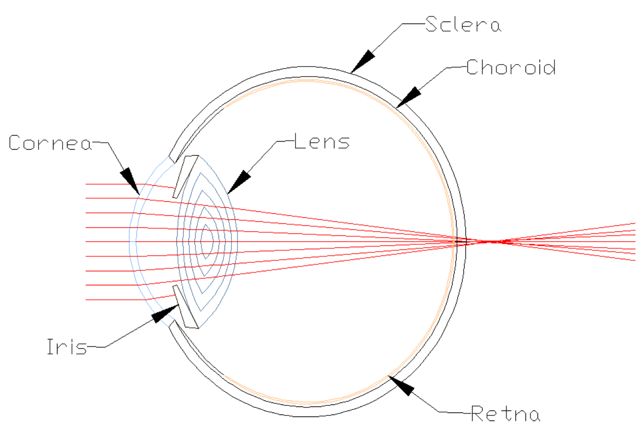

Figure 4: Layered Lens, $n_l \approx 1.386\ to\ 1.406$

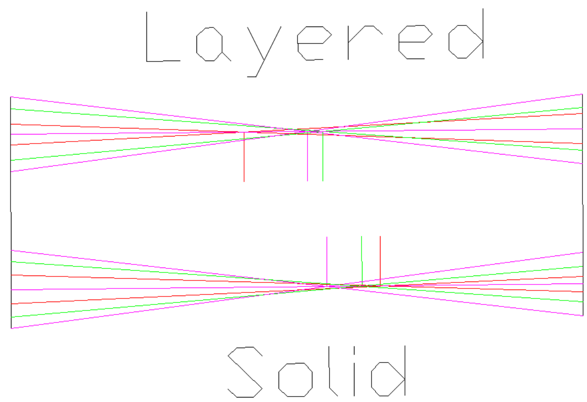

Figure 5: Detailed view of the crossing of the optical axis by various rays through the lens.

this will vary from individual to individual. Since my model is not adaptive like this, it is no surprise that it doesn't happen to work out with the approximate dimensions involved. Figure 4 shows a contrived 'layered' lens with five layers which range from an index of refraction of 1.386 to 1.406. Note that at each layer Snell's law as repeatedly used to obtain the new bearing of the light rays. To more carefully compare the difference between these two types of lenses a closer investigation of the circle of least confusion was done (Figure: 5). For a simple homogenous spherical lens, the light that is focused from the outside of the lens tends to cross the optical axis earlier than light rays near to the center of the lens. The model demonstrated that this is not the case for a layered lens. In fact, with carefully designed surfaces, the spherical aberration may be completely corrected.

The layered nature of the lens provokes exploration into the idea of 'flat' lenses. I spent some time investigating the requirements of such a lens, beginning with a spherical lens, applying Snell's Law, and allowing for a variable index of refraction. Theoretically, as the surface becomes flat, Snell's Law suggests that light cannot be refracted back to the optical axis (Without a negative index of refraction). However, the variational principle implies that as long as a stationary optical path is achieved, light will "follow" that path. Requiring light to travel through a different distance of glass depending on the distance from the optical axis is actually only one way of adjusting the time that the light is 'slowed' in the glass. If, instead, the thickness of a lens is left stationary and the time that the light is 'slowed' in the lens is adjusted by variation in the index of refraction, the same effect could be achieved.

Though it is unlikely that these are the only advantages of the layered lens, these two reasons alone indicate the advantage of the adjustability built in to biological systems. In section 4 I describe some of some possible implications for modern lens design based (loosely) on this concept.

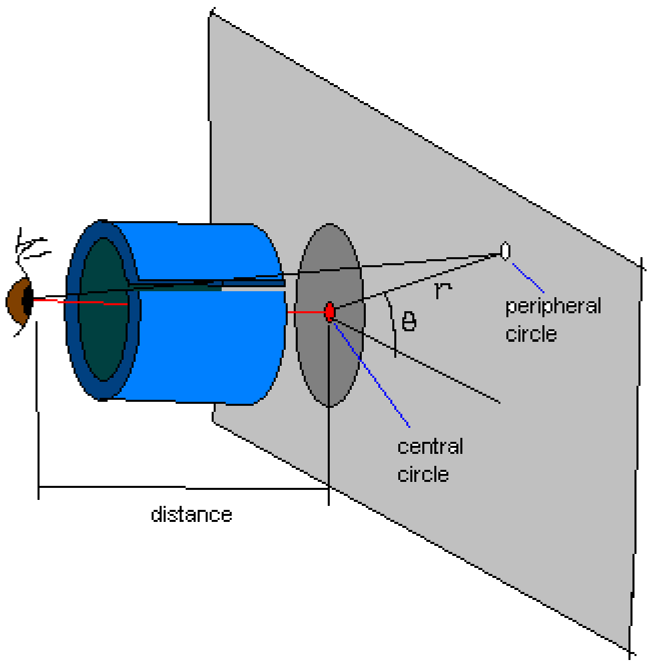

Figure 6: Experimental apparatus

Peripheral Vision I found it very difficult to narrow down my research to a property of the eye that could be experimentally measured. An aspect of humans that I've always found curious is the tendency for a person to make dramatic proclamations about his or her deviation from 'normal' sensation of the world. For example, I've heard people say, "I see colors very vividly!", or "I have a photographic memory!", or "My depth perception is very good!", or "I've got very good peripheral vision!". When I hear people say things like that I immediately think to myself, "How did they measure?". So I decided to try to measure these things for myself. When I considered the endless list and incredible complexity of assessing claims like this, I finally decided that I would reduce my measurement to peripheral vision.

Experimental Setup - In order to measure the angle at which the eye can sense light, the position and orientation of the eye needs to be fixed. To do this, I created a simple pipe 50mm long with a 50mm diameter and a slit along one side. Using Matlab I made a program that could draw a circle on the screen exactly 50mm in diameter, with another small circle (The central circle) drawn in the center. Thus, if the pipe was placed on the screen at this circle, and the eye was pressed against the end of the pipe and focused on the central small circle, the orientation of the visual axis could be fixed and the distance from the screen to the eye could be fixed (Approximately). See figure 6.

To allow for peripheral sensitivity to be compared at different angles, the orientation of the slit could be adjusted to allow vision at a particular viewing angle. Further, the Matlab program was designed to draw another small circle (The peripheral circle) at a certain distance from the central circle. This formed an approximately right triangle between the eye, the central circle, and the peripheral circle. The distance and angle from the central circle to the peripheral circle could be adjusted to allow measurements of the peripheral vision.

Experimental Results - There were several issues with the experiment mostly stemming from the complexity of the visual system.

One is the fact that the eye is a dynamical system, always adjusting the pupil and the lens and even involuntarily 'twitching' the optical axis. Obviously as the pupil adjusts, peripheral vision adjusts with the greatest angular sensitivity coming when the pupil is wide open. The lens also affects the peripheral vision as it adjusts focus. Since my experiment required the object to be only 50mm from the eye, it could not adequately focus. The attempts to do so caused an even stronger dynamic quality in the experiment. The twitching adds a probabilistic element to the study since there is a probability that the visual axis will twitch up causing a reduction in the angle to the peripheral circle or to twitch down causing an increase in the angle.

Second to this dynamical aspect of the experiment, there is trouble because of the variation of density of the retina on the interior of the eyeball. The further away from the fovea, the less dense the retina. Thus, there is a natural 'fading out' of the periphery. Combining this with the complexity of the image processing in the brain, there is no true 'edge' of the vision. Though it makes up only 2 or 3 percent of the retinal surface, the macula lutea commands about 50% of the processing power of the visual cortex. Thus there is an apparent 'mental' fading in addition to the physical fading. The retina becomes less sensitive to colors and then to shapes and finally is sensitive only to changes in intensity making it difficult to define exactly what is meant by 'visual boundary'.

The last issue that retarded the experiment was the shear quantity of measurements that needed to be taken. To precisely determine if light can be detected at a particular point, it appeared to be necessary to test a subject (In this case myself) with a stochastic process in which one could not predetermine where or when the light would appear. For a reasonable determination of the probability that the brain recognizes light appearing at a particular point, at least 10 tests at the point seemed necessary. With the thousands of possible points at different radii and angles (See figure 6), this became too tedious and time consuming and because of the other drawbacks did not seem to be worth the necessary time investment.

4 Conclusion

This research project was an enlightening exploration into the nature of the human eye that left me much more intrigued by biological systems. I have gained a new determination to continue studying the eye as well as the various other systems of the human body. The apparent 'cleverness' of nature offers ideas that people can take advantage of to solve engineering problems that have no connection to biology.

For example, the layered nature of the lens provokes exploration into the idea of 'flat' lenses. Further understanding of how the body achieves a graduated index of refraction in its layers may provide ideas for easily creating similar gradients, allowing for a much greater flexibility in lens shape. I have become fascinated by the design process of nature. It is more or less and iterative stochastic approach. With the development of computers in the past few decades, it seems that the need for simplifying the design process by making predeterminations such as the use of 'spherical lenses' is unnecessary. I propose that algorithms could be written to create complex lenses with variable geometry and index of refraction to approximate optimal specifications. Hopefully these could be based on the variational principle rather than the more restricting concept of Snell's Law. Taking advantage of the modern manufacturing techniques used in the semi-conductor industry it seems plausible that almost any configuration determined by the algorithm could be realized. This would be a fantastic area of research.

As far as the experimental measurements that I intended to make on peripheral vision, I am afraid that more elaborate equipment would be required in order to achieve satisfying results. I did discover that taking advantage of the eyes ability to center themselves consistently on the optical axis could simplify the equipment a great deal. However, the directional nature of an LCD monitor made the determination of sensitivity and different angles impractical. As a substitute I suggest that sort of curved screen should be used that could be fixed in position relative to the head and curved around the head at a fixed radius. This would only need to be a segment of a sphere that could be rotated to measure sensitivity and varying angles off of vertical. The time required for data collection could be reduced a great deal if a general estimate of the 'edge' of peripheral vision was determined so that measurements would only be required near to this boundary. To overcome the lack of a simple definition for the 'boundary of vision', different types of measures could be made. There is a different boundary for knowing whether or not a flash of light occurs than the boundary for distinguishing between the shape of a circle and a square (As an example).

Though upon beginning my research I had hoped to see a sharp image of the human visual system, I have not achieved this goal. However, it is at least satisfying to have gained knowledge of the pieces involved. Above all I have been impressed by my lack of knowledge in this area and have been stimulated to seek this same general knowledge for more of the systems in the body.

References

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