Chapter 9

Physics of the Eye

In this laboratory session we shall examine the operating principle of a human eye. Eyes convert traveling electromagnetic waves (light) into electro-chemical signals which the brain then processes into an image. Although light is a wave, we will focus on geometric (ray) optics for this explanation, and not concern ourselves with wave-optical effects such as diffraction and interference.

Note: Many of the exercise below were adapted with permission from a lab manual created by PASCO Scientific, the company who designed the equipment you will be using in this lab.

9.1 Background

9.1.1 How Lenses form Images

Light rays are bent, or refracted, when they cross an interface between two materials that have different indices of refraction. The **index of refraction** of a material is the ratio of the speed of light in a vacuum to the speed of light in the medium. Light passing through a lens crosses two such interfaces: one where it enters the lens at the front surface, and another where it leaves the lens at the back surface.

Lenses and Focal Length

The amount by which light is bent is quantified by the lens's **focal length**. A strong lens, which can bend rays so that they intersect at a short distance, is said to have a short focal length. A weaker lens bends rays less, so that they intersect further away, and is said to have a long focal length. If the incoming rays are parallel, the distance at which the outgoing rays intersect is equal to the lens's focal length.

The focal length of a lens is determined by the curvatures of the its front and back surfaces, its index of refraction, and the index of refraction of the material surrounding the lens. A lens with highly curved surfaces usually has a shorter focal length than one with flatter surfaces made from the same material. A lens with a high index of refraction has a shorter

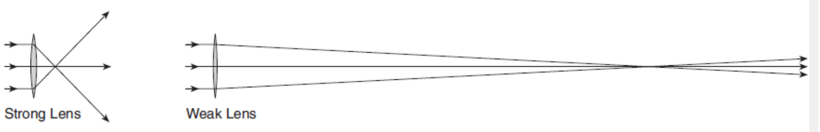

Figure 9.1: Qualitative description of lenses.

focal length than an identically shaped lens with a low index of refraction. A lens surrounded by air (which has a low index of refraction) has lower focal length than the same lens immersed in water (which has a high index of refraction).

There are two types of lenses: convergent and divergent (See Fig. 9.2). A **convergent lens** makes incoming parallel rays converge, or come together. A convergent lens typically has a convex surface and is thicker at the center than at the edge. The focal length of a convergent lens is positive. A **divergent lens** makes incoming parallel rays diverge, or spread apart. A divergent lens typically has a concave surface and is thinner at the center that at the edge. The focal length of a divergent lens is negative.

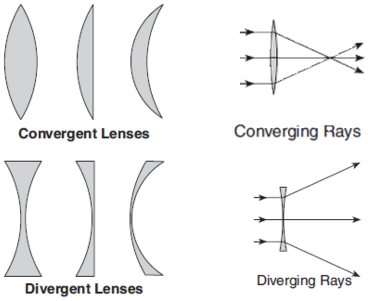

Figure 9.2: Converging and Diverging Lenses

Images and Image Distance

When an object is placed in front of a lens, the light from the object passing through the lens forms an image. There are two types of images: real and virtual. A textbfreal image is formed by converging rays at the point where they intersect. A real image can viewed on a screen placed at that point, and you can see it directly if you place your eye behind that point. A **virtual image** is formed by diverging rays at the point where imaginary lines drawn through the rays intersect. If you allow these diverging rays to enter your eye, you will see the virtual image located at the point where the rays appear to be coming from.

The distance from the lens to the image is called the **image distance**. A real image is formed behind the lens and has a *positive* image distance. A virtual image is formed in front of the lens and has a *negative* image distance.

9.1.2 Objects and Object Distance

Lenses focus light from an **object**. The distance from the lens to the object is called the **object distance**. In a single-lens system, the object is placed in front of the lens and the object distance is positive.

In a two-lens system as shown in Fig. 9.3, the object focused on by the second lens is the image (either real or virtual) formed by the first lens. If this object is in front of the second lens, the object distance is positive. If the object is behind the lens, the object distance is negative.

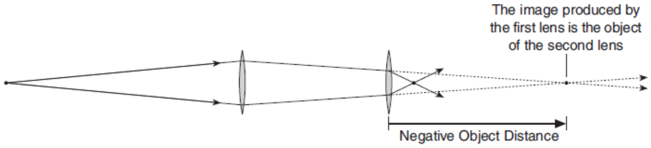

Figure 9.3: A system with two lenses.

Thin Lens Formula

The focal length of a lens (f) is related to object distance (d_o) and the image distance (d_i) by the Thin Lens Formula:

$$\frac{1}{f} = \frac{1}{d_i} + \frac{1}{d_o} \tag{9.1}$$

If the object is very far from the lens, the object distance is considered to be infinity. In this case, the rays from the object are parallel, $1/d_o$ equals zero, and the image distance equals the focal length. This leads to the definition of the focal point as the place where a lens focuses incoming parallel rays from a distant object. A lens has two focal points, one on each side. The distance from the lens to each focal point is the focal length.

Magnification

The size of an image can be different from the size of the object. The magnification, M , of the image is defined by:

$$M = \frac{imagesize}{objectsize} \tag{9.2}$$

If M is greater than 1, the image is larger than the object; if M is less than 1, the image is smaller.

The magnification, M, which can be positive or negative, represents both the size and orientation of the image. It can be defined in terms of the image and object distances:

$$M = -\frac{d_i}{d_o} \tag{9.3}$$

If M is positive, the image is upright, or in the same orientation as the object. If M is negative, the image is inverted, or in the opposite orientation to the object. If the object is right-side-up, then the inverted image appears upside-down.

9.1.3 Power

The power of a lens is measured in units called diopters. To calculate a lens's power in diopters, take the reciprocal of its focal length in meters.

$$Power = -\frac{1}{f} \tag{9.4}$$

9.1.4 Anatomy of the Eye

The human eye (See Fig. 9.4) achieves vision by forming an image that stimulates nerve endings, creating the sensation of sight. Like a camera, the eye consists of an aperture and lens system at the front, and a light-sensitive surface at the back. Light enters the eye through the aperture- lens system, and is focused on the back wall.

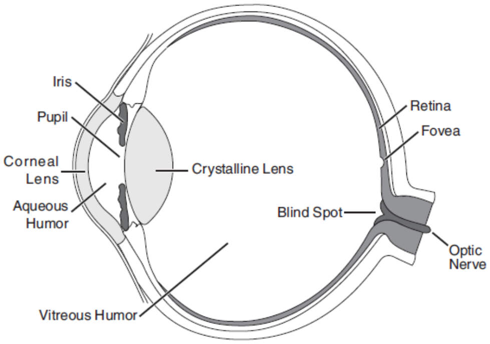

Figure 9.4: Horizontal cross section of the human eye.

The lens system consists of two lenses: the **corneal lens** on the front surface of the eye, and the **crystalline** lens inside the eye. The space between the lenses is filled with a transparent fluid called the **aqueous humor**. Also between the lenses is the **iris**, an opaque, colored membrane. At the center of the iris is the **pupil**, a muscle-controlled, variable- diameter hole, or aperture, which controls the amount of light that enters the eye.

The interior of the eye behind the crystalline lens is filled with a colorless, transparent material called the **vitreous humor**.

On the back wall of the eye is the **retina**, a membrane containing light-sensitive nerve cells known as rods and cones. Rods are very sensitive to low light levels, but provide us only with low-resolution, black-and-white vision. Cones allow us to see in color at higher resolution, but they require higher light levels. The **fovea**, a small area near the center of the retina, contains only cones and is responsible for the most acute vision. Signals from the rods and cones are carried by nerve fibers to the **optic nerve**, which leads to the brain. The optic nerve connects to the back of the eye; there are no light-sensitive cells at the point where it attaches, resulting in a **blind spot**.

9.1.5 Optics of the Eye

The corneal lens and crystalline lens together act like a single, convergent lens. Light entering the eye from an object passes through this lens system and forms an inverted, real image on the retina.

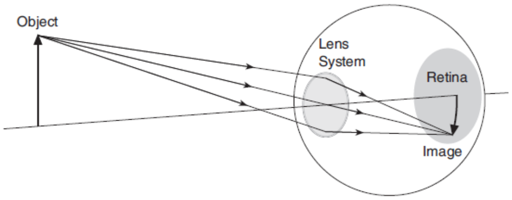

Figure 9.5

The eye focuses on objects at varying distances by **accommodation**, or the use of muscles to change the curvature, and thus the focal length, of the crystalline lens.

In its most relaxed state, the crystalline lens has a long focal length, and the eye can focus the image of a distant object on the retina. The farthest distance at which the eye can accommodate is called the *far point* for distinct vision. **For a normal eye, the far point is infinity.**

When muscles in the eye contract and squeeze the lens, the center of the lens bulges, causing the focal length to shorten, and allowing the eye to focus on closer objects. The nearest distance at which they eye can accommodate is called the *near point* for distinct vision. **The near point of a normal eye is about** $25cm$**.**

9.1.6 Visual Defects and their Correction

A normal eye can focus by accommodation on any object more than about $25cm$ away. In cases where an eye cannot focus on an object, the image is formed either behind or in front of the retina, resulting in blurred vision. This can be caused by the eye being too short or too long.

Near-Sightedness (Myopia)

A person affected by **myopia** has an eye ball that is too long (See Fig. 9.6), making the distance from the lens system to the retina too large. This causes the image of distant objects to be formed *in front* of the retina. The far point of a myopic eye is less than infinity.

A myopic eye can naturally focus divergent rays from a near object on the retina, but not parallel (or nearly parallel) rays from a distant object. Eyeglasses that correct myopia have a divergent lens, which forms a virtual image of the distant object closer to the eye.

Far-Sightedness (Hypermetropia)

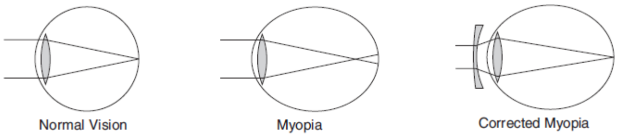

Figure 9.6

A person affected by **hypermetropia** has an eye ball that is too short, making the distance from the lens system to the retina too small. This causes the image of near objects to be formed *behind* the retina. The near point of a hypermetropic eye is greater than normal.

A hypermetropic eye can naturally focus parallel (or nearly parallel) rays from a distant object on the retina, but not highly divergent rays from a near object. Hypermetropia can be corrected using eyeglasses that have a convergent lens, which reduces the divergence of incoming rays.

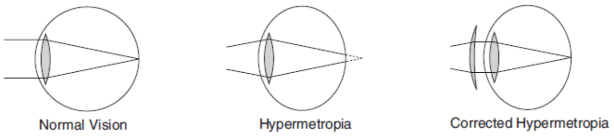

Figure 9.7

A form of hypermetropia called **presbyopia** (old-sightedness) is not caused by the shape of the eye, but by a change in the crystalline lens: over time, the lens becomes more rigid, making it less able to accommodate to short object distances.

9.2 Experiment: Optics of Human Eye

In this experiment you will study how images are formed on the retina of the eye.

9.2.1 Prelab Exercises

1. Draw a diagram of the eye and identify the corneal lens, pupil, iris, crystalline lens and retina. Hint: use Fig. 9.4 as a guide.

9.2.2 Images Formed in the Eye

Before you start, take a close look at the eye model and identify the parts of the human eye represented by each part of the model. (ex. corneal lens, retina screen)

1. Do not fill the eye model with water yet. Put the retina screen in the middle slot, marked NORMAL as shown in Fig. 9.8. Put the +400 mm lens in the slot labeled SEPTUM.

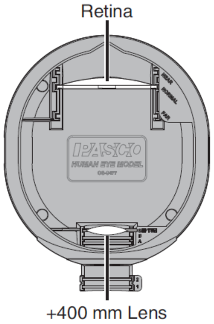

Figure 9.8

2. Put your hand in front of the eye model, about 50 cm from the cornea. Use your desk lamp to brightly illuminate your hand. Can you see an image on the retina screen? Move your hand up, down, left, and right. How does the image move?
3. Using the supplied asymmetrical picture on a sheet of paper, hold it in front of the eye model. Is the image of your picture on the retina inverted? Turn the picture upside down. How does the image look now? Sketch the retina image and draw a copy of the original picture next to it.

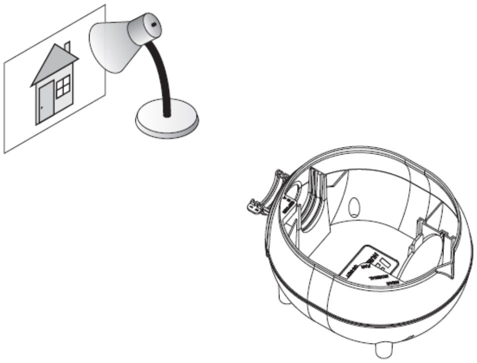

Figure 9.9

4. Write something on a piece of paper and hold it upside down in front of the eye. How does it look on the retina? Are you able to read it easily?

9.2.3 Accomodation

In the process of accommodation, muscles in the eye change the shape of the crystalline lens to change its focal length. Initially, you will model accommodation by varying the focal length of the crystalline lens using the adjustable focus lens. Later, when the model is filled with water, accommodation is achieved by replacing the crystalline lens with fixed lenses of various focal lengths.

Procedure

1. Do not fill the eye model with water yet. Replace the lens in the SEPTUM slot with the adjustable focus lens. Position the illuminated screen about $25cm$ from the eye model. Can you see the image on the retina? **Very gently and slowly**, move the syringe plunger to adjust the lens and form the **clearest image possible**. Is the lens concave or convex? Is it a converging lens or a diverging lens?

2. Move the screen farther from the eye model to about $50cm$. **Gently**, adjust the lens again to form the clearest image. Did you increase or decrease the power of the lens? Did you increase or decrease the focal length?

3. Replace the adjustable focus lens with the $+400mm$ lens in the SEPTUM slot. Adjust the distance of the illuminated screen to form a clear image. Using a beaker, fill the eye model with water to within 1 or $2cm$ of the top. Is the image still in focus? Try changing the distance; can you get it to focus? Explain. What effect do the aqueous and vitreous humors (modeled by the water) have on the focal length of the eye's lens system?

4. Place the light source about $35cm$ from the eye model. Replace the $+400mm$ lens in the SEPTUM slot with the +62 mm lens. Is the image in focus now? Move the light source as close as possible to the eye model while keeping the image in focus. Describe the image on the retina screen.

5. The optics of a two-lens system can be simplified by looking at the combined effect of the lenses and the total effective focal length of the system. Measure the image distance (d_i), from the model's rim to the handle of the retina. Measure the object distance, d_o, from the screen of the light source to the top rim of the eye model, as shown in Fig. 9.10. (The front of the rim is a convenient place to measure to and marks the center of the eye model's two-lens system.) Record this distance, which is the near point of the eye model when equipped with the $+62mm$ lens. Calculate the total effective focal length (f) of the two-lens system using the thin lens formula, Eq. 9.1.

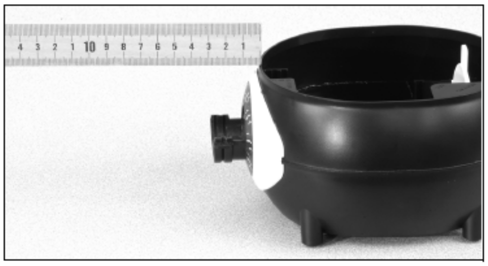

Figure 9.10: The correct way to measure object distance using the PASCO eye model.

6. Increase the ability of the eye model to focus on a close object by adding the $+400mm$ lens to slot B. This combination models a different focal length for the crystalline lens. How close can the eye focus now?

7. Keep the $+400mm$ lens in slot B and replace the lens in the SEPTUM slot with the +120 mm lens. At what distance does the model eye focus now? What does a real human eye do to change the focal length of its crystalline lens?

8. Remove both lenses and place the $+62mm$ lens in the SEPTUM slot. Adjust the eye-source distance to the "near point" distance for this lens (which you found in step 6) so that the image is in focus. While looking at the image, place the round pupil in slot A. What changes occur in the brightness and clarity of the image? Move the light source several centimeters closer to the eye model. Is the image still in focus? Remove the pupil and observe the change in clarity of the image.

9. Carefully rotate the eye model (with pupil removed) so that it is looking towards a *distant* object. Is the image on the retina in focus? Replace the lens in the SEPTUM slot with one that makes a clear image of the distant object; this is the farvision lens. Record the focal length marked on the handle of the lens.

10. Calculate the total effective focal length of the lens system, as you did in step 5. What value should you use as the object distance for far vision? How do you enter that value into a calculator? (Hint: as the object distance, d_o, increases towards infinity, the inverse of the object distance, $1/d_o$, decreases towards zero.)

11. One treatment for cataracts is to surgically remove the crystalline lens. Remove the crystalline lens from the eye model and observe the image of the distant object on the retina. Can an unaided eye without a crystalline lens focus on distant objects?

    Place the +400 mm lens in slot 1 to act as an eyeglasses lens. Does this restore clear vision? Rotate the eye model back to facing the light source. Can you adjust the near object distance to form a clear image? Replace the eyeglasses lens in slot 1 with the +120 mm lens. Now can you adjust the object distance to form a clear image?

Questions:

1. Compare the crystalline lens needed for far vision to the crystalline lens needed for near vision? Which lens is more curved? When you look through them, which lens appears to be stronger? Compare the effective focal lengths (of the two-lens systems) for near and far vision that you calculated in steps 5 and 10.

2. In a real human eye, accommodation is accomplished by muscles that change the curvature of the crystalline lens. When an eye changes accommodation from a distant object to a near object, does the curvature of the crystalline lens increase or decrease?

9.2.4 Far-sightedness (Hypermetropia)

A person affected by hypermetropia has a shorter-than-normal eye ball, making the retina too close to the lens system. This causes images of near objects to be formed behind the retina.

Procedure

1. With the eye model filled with water, set the eye model to normal near vision (put the $62mm$ lens in the SEPTUM slot, remove other lenses, and make sure the retina is in the NORMAL position). Position the eye to look at the nearby light source. Adjust the eye-source distance to the near-point distance so that the image is in focus.
2. Move the retina screen to the forward slot, labeled FAR. Describe what happens to the image. This is what a far-sighted person sees when trying to look at a near object. Decrease the pupil size by placing the round pupil in slot A. What happens to the clarity of the image? Remove the pupil.
3. Carefully turn the eye model to look at the distant object, and describe the image. Does a far-sighted person have trouble seeing distant objects? Why was it not necessary to change the lens to look far away?
4. Return the eye model to looking at the nearby light source. You will now correct the hypermetropia by putting eyeglasses on the model. Find a lens that brings the image into focus when you place it in front of the eye in slot 1. Record the focal length of this lens.

   Rotate the eyeglasses lens in the slot. Does this affect the image on the retina?
5. A corrective lens is not usually described by its focal length, but rather by its light-bending power. Using equation 9.4, what is the power of the eyeglasses lens that you selected for the model eye?
6. Make sure that the image is still in focus. Remove the eyeglasses. Add the $+120mm$ lens in slot B to simulate what happens when the crystalline lens increases its power by accommodation. Does the image become sharper? This shows that the eye can compensate for hypermetropia if it can accommodate sufficiently.

Questions:

1. Why did reducing the pupil size make the image clearer? Would a person with hypermetropia see better in bright light or in dim light?
2. Does a strong lens (high power) have a long or short focal length? What are the power and focal length of a thin, flat piece of glass with no curvature? Look carefully at the $+62mm$ and $+400mm$ lenses. Which lens has the greater curvature?
3. To correct hypermetropia, is it necessary to move the image formed by the eye closer to or farther from the eye's lens system? Does this require a convergent or divergent lens? Does this corrective lens add to or subtract from the light-bending power of the eye's lens system?

END OF LAB

Was this lab useful, instructive, and did it work well? If not, send an email to thatlabsucked@gmail.com and tell us your issues. In the subject line, be sure to reference the your course, the experiment, and session. example subject: *PHYS1010 Linear Motion monday 2:30*. We won't promise a response, but we will promise to read and consider all feedback.