Simple Experiments on the Physics of Vision

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(English translation of the article published in **Alambique**, **39**, pp. 93-98, 2004)

The experiments related to the physics of perception, particularly those concerning the visual system, are particularly attractive: by using only extremely simple materials it is possible to get amazing results.

The experiments based on the working of the eyes can be easily understood from the basic principles of geometrical optics. The analysis of what happens in the retina after the light has activated the sensors is a much more complex subject and this complexity increases as the impulses transmitted by the optic nerve propagates in the brain through the successive stages where their analysis is performed[1].

Many experiments based on visual illusions are difficult to analyze since, often, these illusions arise from the treatment of the signals in the nervous cells of the retina and in the brain[2]. Thus, only the experiments based on the "optical components" of the eye will be discussed here. Even so, the range is quite broad and only the most relevant ones have been quoted.

Experiments

The only materials needed are a square piece of black cardboard (about 4x4 cm) and a pin. A pinhole has to be made in the cardboard about the same diameter as the pin. This is the most convenient diameter if the experiments have to be done outdoors. Otherwise, perhaps the hole must be enlarged a bit if the experiments are done indoors. Since in many experiments a white and well lighted surface is required, in the classroom or in the lab an slide or overhead projector can be used to light a white screen; outdoors, the blue sky works perfectly.

The structure of the eye, with a few anatomical terms used along this article, is shown in figure 1. The experiments have been gathered following the characteristics of the eye that are being explored.

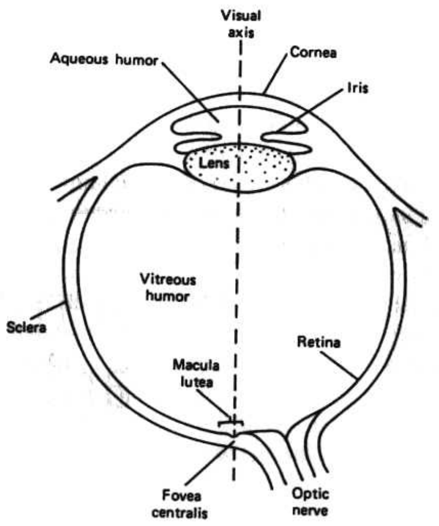

Figure 1. Structure of the eye

1. **Liquids in the eye**.

The eye contains two converging lenses, the cornea and the crystalline lens. Since they are transparent and colorless alive tissues, the nutrients do not reach these tissues by means of the blood, as happens in a normal tissue, but dissolved in the liquids contained in the eye (the vitreous and aqueous humors) that keep it under a small pressure as if it were a balloon. These aqueous dissolutions flow bringing nutrients and removing waste metabolites. Glaucoma, a serious condition, is due to an increase of the pressure of these liquids that can cause the retina to suffer a gradual and irreversible damage.

Experiment: Cells floating in the liquids in the eye.

A white surface well lit (or the blue sky) is observed, using only one eye, through the pinhole of the cardboard, put just in front of the eye. The pinhole works as a point source that casts well defined shadows of anything moving into the liquids in the eye, particularly, groups of dead cells and lumps of gelatinous substances (floaters) with elongated and globular shapes. The sharpness of the shadows of these floaters due a point source contrast with the diffuse shadows seen with the usual extended sources of light.

It is easy to check that shaking the head there is an increase in the random movement of the floaters. Since they float in the liquids any attempt to control their movement or simply to keep them in the visual field is unsuccessful.

2. **Lenses in the eye**[3-5] .

The cornea works between air and "water" (aqueous humor) whereas the crystalline lens, which is an alive tissue with a high percent of water, has to work between "water" and "water" (aqueous humor and vitreous humor) . Thus, out of these two lenses, the cornea is the one that makes the most of the work, consisting of bending the light and forming an image on the retina. The cornea has a fixed shape whereas the curvature of the crystalline lens can be changed by means of the actions of muscles (accommodation). This change of shape allows focusing objects at different distances since the combined power of cornea and lens can be changed from about 59 to 70 dioptres (in young people) . This range of accommodation depends greatly on the age: children can have a range of accommodation up to 14 dioptres, but in the elder this range can be almost 0. In a camera the lens have a fixed curvature and the focusing is made changing their distance to the film.

Experiment: Accommodation

Two objects at different distances in the visual field cannot be focused simultaneously. If you extend your arm and focus to a finger, the background is out of focus. If you focus into the background, the finger is out of focus. The effort made with the muscles that act on the lens (and the muscles changing the convergence of the eyes) can be perceived.

Experiment: The image on the retina is inverted[6,7]

Both lenses in the eye are convergent, thus, the images corresponding to objects farther from the focal distance (about 1.5 cm) are inverted on the retina.

As shown in figure 2, a well lit white surface (or the blue sky) is observed, using only one eye, through the pinhole of the cardboard, about 10 cm in front of the eye. The pin has to be hold upright just in front of the eye (caution!). In this experiment it is advantageous to wear glasses since the pin can touch the glass without any danger. The pin and the pinhole have to be aligned so that the pupil, the head of the pin and the pinhole lie in a straight line. Surprisingly, the head of the pin, seen against the clear background through the hole is seen upside down, hanging with a mushroom shape. (figure 3)

This result can be explained in a simple way (figure 4) if we consider two points A and B (as if they were two small bulbs) seen through the pinhole, that works like a pinhole camera: A beam of light coming from the upper bulb, A, goes towards the lower part of the pupil. With the pinhead in the lower position, we can intercept selectively the beam of light coming from A so that these rays of light cannot enter the eye and what we see is the absence of A; in other words, instead of A we see the shadow that the pin casts.

What is demonstrated with this experiment is that, despite we see an object in the upper part of the mental representation of the world outside us, the position of the image of this object is in the lower part of the retina: the light directed towards the lower part of the retina forms an image in this lower part, and we are able to block it with the pin.

Figure 2. Position of the cardboard and the pin to observe the inverted shadow.

Figure 3. Actual photograph of the inverted shadow of the pin, corresponding to figure 2.

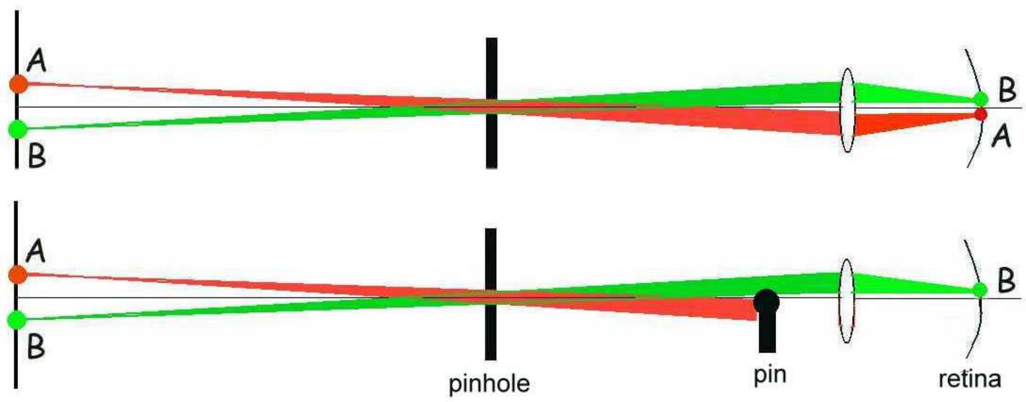

Figure 4. Path of the rays from two points A and B. By means of the pinhole in the cardboard , the pin can block selectively light rays coming from A or B. The shadow corresponding to the blocked rays appears inverted.

3. **Pupil: The diaphragm of the eye**.

Between the cornea and the lens there is a diaphragm, the pupil, whose aperture not only controls the amount of light entering the eye but also contributes to focusing: a small pupil increases the depth of field depth and we can see with an acceptable focusing near and far objects.

Experiment: Joint reaction of the pupils to a change in the intensity of light[8]

A well lit screen or the bue sky is observed through the pinhole (not very near to the eye, at about 1 cm), with both eyes open. The other eye is successively covered and uncovered with the hand at a pace of about 5 seconds. The width of the visual field shrinks as the hand is removed and expands when the hand covers the eye as if the pinhole changed of size. This happens because both pupils work together: when one eye is covered the total amount of light entering the eye decreases and both pupils expands; on the contrary, both the pupils shrink as one eye is uncovered. If the experiment is done watching a wall with rows of bricks, the number of visible rows changes as the pupil changes its size.

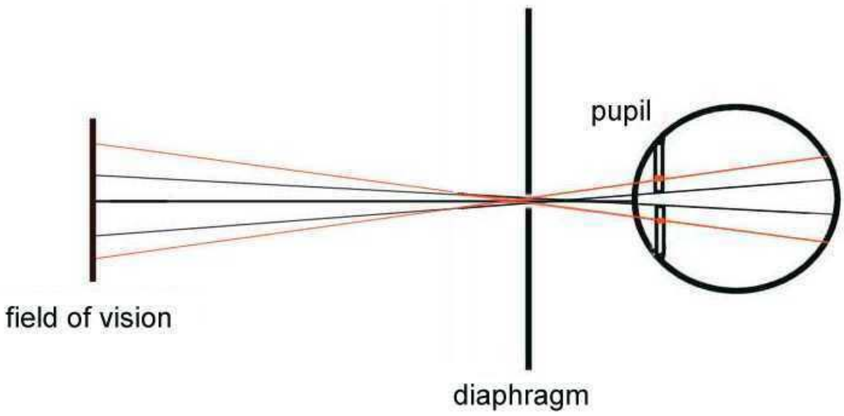

Figure 5. Change in the width of the vision field through a pinhole, due to changes in the size of the pupil.

Experiment: Depth of field

Observe the head of the pin using only one eye. As it is approached to the eye, we can check the position of the near point at about 20 cm of the eye (or more, depending of the age) . The pin cannot be seen well focused at 5 cm or even at 10 cm.

Next, the pin is observed again with one eye, this time through the pinhole. In this case the pin can be approached very much and even at short distances it can be seen with a reasonable sharpness.

It can also be checked as, without the pinhole, if you look at a finger in your extended arm aimed to some object in the background, only one of them: the finger or the object is seen focused. It is not possible to focus both of them simultaneously. When the pinhole is used, the finger and the background can be seen with enough sharpness.

The effect of a small diaphragm (the pinhole, in this experiment) is to increase the depth field. Thus, the objects in a broad range of distances can be focused simultaneously. This is the trick of the cheapest cameras in which there is not any adjustment: a small diaphragm allows everything from 1 m to infinite to appear focused.

Those suffering from presbyopia (a loss of elasticity of the lens that reduces the range of accommodation and increases the distance of the near point) know that a very intense light makes reading easier: the pupils closes and the depth of field increases making it possible to focus the newspaper even if it is approached.

To understand why this happens we have to consider that there is not a way to focus perfectly to objects at different distance of a lens. The trick is reducing their blurring so that in an intermediate position of a screen they can be seen with enough sharpness. Figure 6 shows the position of the images corresponding to two objects at different distances from a converging lens. With a big diaphragm (or not diaphragm at all) there are big cones of light collected by the lens and directed towards the position of the image. So, it is impossible to find a position of a screen giving well defined images of both objects. Using a small diaphragm the images are produced in the same position as before but the narrower cones of light allow finding a position in which, despite there is not a perfect focusing, the blurring in the images of both objects is tolerable and they are seen almost focused simultaneously.

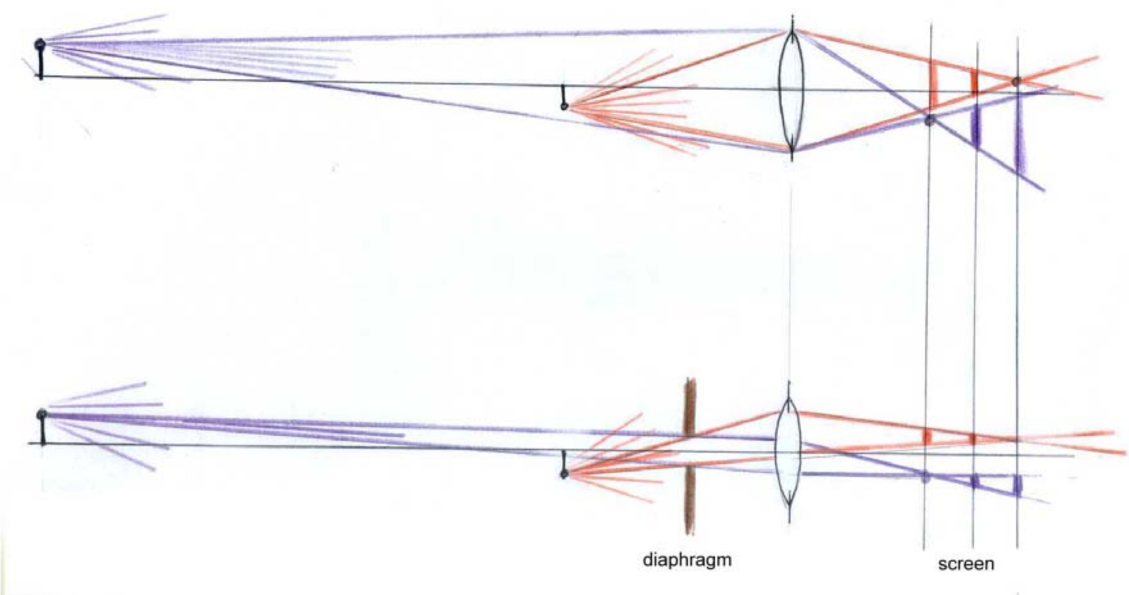

Figure 6. The blurring in the images of both objects is reduced with a diaphragm. Without diaphragm there is no a position where both objects can be seen focused. With diaphragm, both objects can be seen reasonable focused (with little blurring) simultaneously.

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