Seeing in the light and in the dark

The human eye is remarkably sensitive. The first stage in the process of seeing is the absorption of light in cells called rods and cones, which lie in the retina, a thin sheet of tissue at the back of the eye. The retina records the image of the world around you somewhat like film does in a camera. Light is composed of small packets of energy called photons, and the eye is so sensitive that the absorption of a single photon is all that is required to stimulate a single rod photoreceptor. If only about 10 rods in a patch of the retina each absorb a photon, a brief flash of light can reliably be seen in the dark. Put another way, the eye is so sensitive that you could deliver 1,000 visible flashes of light to every person who ever lived with the energy required to lift a pea an inch off your dinner plate. On the other hand, our eyes can also operate at light levels much brighter than this. For example, a white piece of paper viewed on a bright sunny day is roughly $10^{11}$ or 100 billion times brighter than the dimmest flashes we can just make out in total darkness.

How does the visual system allow us to see so clearly over such an enormous range of light intensities? This operating range is all the more impressive because the retina sends visual information to the brain with optic nerve fibers that have a very limited operating range. These nerve cells send impulses to the brain at a rate that increases with the intensity of light. However, their useful range is from perhaps a few spikes/sec to 200 spikes/sec, or a range of about 100/1. How can the $10^{11}$/1 range of light intensities be compressed into a range of 100/1? Some simple experiments you can perform with your own eyes provide some clues.

Changing pupil size

One trick the visual system uses is to change the size of the pupil, depending on the light level. In the dark, the pupil dilates, letting in roughly 10 times more light than it does when it is constricted in bright light. Watch someone’s pupils when they are standing in a dimly lit room. Illuminate one of his eyes with a flashlight, while shielding the light from the other eye. You can change the size of the pupil of the unilluminated eye by changing the amount of light to the illuminated eye. The pupils of the two eyes are about the same size no matter how differently the eyes are illuminated, indicating that they are yoked together by a single mechanism that controls both eyes.

Changing from cones to rods

Another way the visual system allows us to see over such a large range of light intensities is to split the task between two distinct sets of photoreceptors: the rods operate at dim light levels and the cones, which also provide color vision, function at higher levels. Roughly speaking, when the rods alone are active, the visual system can be a thousand times more sensitive than when the cones are active.

The enhanced sensitivity of the rod system comes at the price of our ability to see fine detail. The visual acuity of the eye when the rods alone are active is about 10 times lower than it is when cones are active. The rod system has an advantage in sensitivity over cones in part because it adds together signals from many rods. The difference in acuity can be observed if you attempt to read under dim illumination. If it is dim enough that the world appears only in shades of gray without color, only your rods are active, and you will be able to read only if the text is very large.

Changing sensitivity

Perhaps the most important mechanism the visual system uses to operate over a large range of light levels is to change its sensitivity depending on the overall light level at any given time. Consider the volume control on a stereo or television. If the sound is too loud, you turn the volume down; if it is too soft, you turn the volume up. The visual system has its own volume control that adjusts itself to different light levels automatically. When the light level increases, the visual system turns down its volume. This process is known as light adaptation. When the light level decreases, the volume is turned up, a process called dark adaptation. We all experience dark adaptation when we step into a dark movie theater from the brightly lit outdoors. Although it is difficult to see initially, after a few minutes your vision seems to improve. This process takes about 30 minutes to complete, though most of the sensitivity adjustment happens within a few minutes.

We are so used to this effortless process that we are rarely aware of it. However, a simple experiment provides a very graphic demonstration of how potent these sensitivity changes of dark adaptation actually are. Find yourself a dark room—the darker the better so long as you can still make out some of the gross features in the room. If you can make out any colors, it is too bright. During the day, a windowless bathroom will do if it is illuminated only by light passing beneath the closed door. At night, a room illuminated only by moonlight is a good choice.

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Make yourself comfortable in this room and notice how objects gradually become easier to see. Wait for at least 5 minutes, though the longer you wait (up to about 30 minutes) the better. Then cover one eye with your hand making sure that no light can get in. Keeping your hand over your eye, turn on all the room lights, or step outside, giving your uncovered eye a full minute to adjust to this new light level. Then return to the dark room and uncover your eye. You should experience a quite dramatic (and slightly disconcerting) difference between your eyes. You will find that you are effectively blind in the eye that was recently exposed to the bright light, though your dark-adapted eye will see the dark room quite clearly.

With this procedure, it is easy to make one eye a thousand times more sensitive than the other eye. Unlike the experiment on the pupils, which work together in the two eyes, this experiment shows that there are separate volume controls, or sensitivity adjustments, for each eye.

After-images

These volume controls are not only independent in each eye, but they also operate relatively independently at different locations within the retina of a single eye. When someone uses a flash camera to take a picture of you, you often notice an after-image of the flash that lingers long after the flash itself. The after-image has the peculiar property that it moves with your eye; no matter where you look, it maintains the same relative position to where you are looking. This is because the after-images originate in the retina, which moves just as the eye moves.

Some kinds of after-images can be thought of as indicators of the volume control settings at different locations in the retina. For example, stare at the center of the “d” in the title of this article. Gaze steadily at the “d” for 20 seconds. Then look at the blank white part of the page just above the title. You should see an after-image of the same letters you saw initially, but this time they will appear brighter than the background instead of darker. These “negative” after-images occur because during the time you were looking at the “d”, the part of the retina beneath the dark letters became more sensitive than the part beneath the bright background. When you shifted your gaze to the uniform white page, the page looked brighter where your retina was most sensitive, so that the letters look bright. Many after-images are a consequence of the normal process the retina uses to adjust to the overall light intensity, allowing us to see in both light and in the dark.