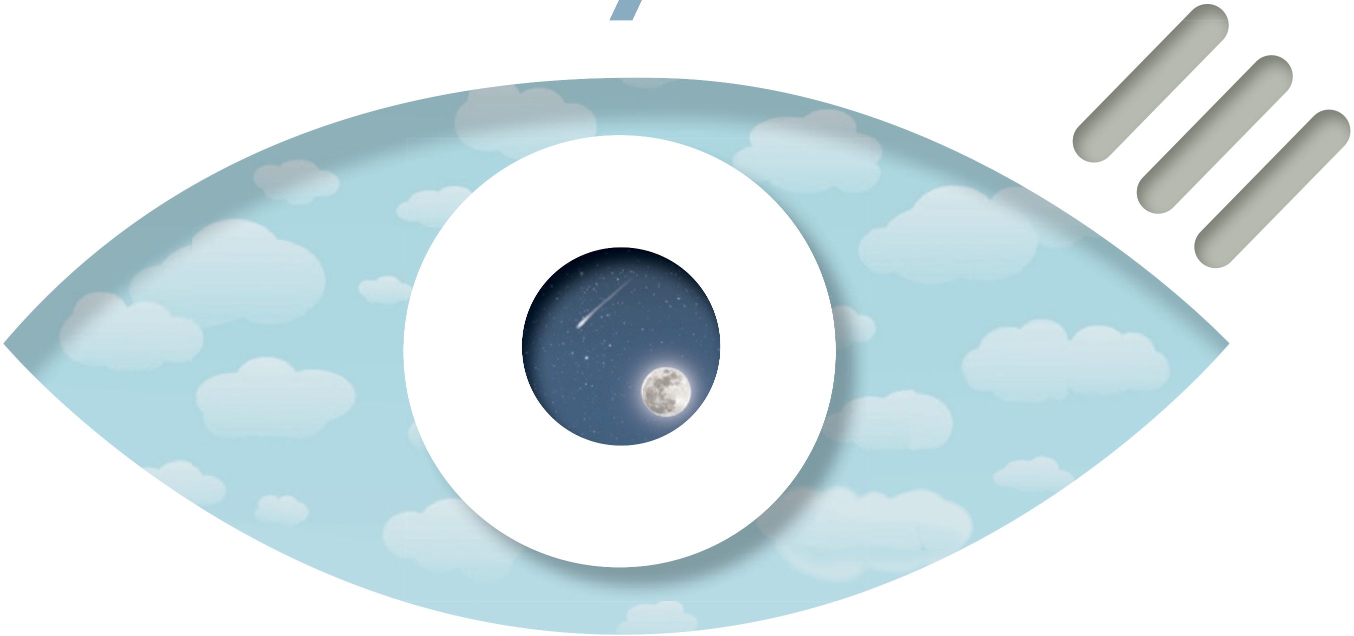
The Sky Within



S&T ILLUSTRATION: PATRICIA GILLIS-COPPOLA

Eye aberrations can have a big effect on visual observing. Here are some tips for seeing the universe more clearly by working with your eyes' imperfections.

When you look naked-eye at the brightest stars in the night sky, do they really look like small pinpoints of light? If your answer is yes, congratulations: you may be among the few people whose eye optics are nearly perfect. But most of us will probably see "hairy" star images if we look carefully. This is nothing unexpected. It's just the most conspicuous effect of eye aberrations.

From an instrument maker's viewpoint, the eye's optics are indeed far from perfect. As the renowned German anatomist and physicist Hermann von Helmholtz (1821–1894) once wrote:

> Now it is not too much to say that if an optician wanted to sell me an instrument which had all these defects, I should think myself quite justified in blaming his carelessness in the strongest terms, and giving him back his instrument.

In an optically perfect eye, all rays coming from a distant point source should be focused to a single point on the retina (see page 70). The human eye is, however, a highly complex living structure, composed of several refracting surfaces and an aperture stop, all kept in place by a combination of tissue rigidity, muscular stress, and intraocular pressure. It's also subject to continuous short-term changes (such as variations in pupil size) and long-term growing processes, such as changes in the size, shape, and internal structure of the eye lens, which cause our vision to alter as we age. The eye's components are somewhat off center and tilted with respect to one another, and their surfaces are deformed in various ways. It would be rather surprising if such a rich biological structure created an absolutely stable and perfect optical system.

In most healthy eyes, light leaving the lens's backside deviates from the shape of an ideal wavefront that is perfectly spherical and focused at the retina. This deviation is called the eye's *wave aberration*. The simplest eye aberrations are nearsightedness (myopia), farsightedness (hyperopia), and astigmatism. These are the smoothest deformations an ideal wavefront can suffer and they change where light focuses in the eye: moving the focal point in front of (myopia) or behind (hyperopia) the retina, or refracting incoming light differently depending on which eye meridian the light passes through (astigma-

Your Eyes

Salvador Bará

tism). Since these deformations can be described mathematically by expressions called second-order polynomials, they are technically termed *second-order aberrations*.

Normal eyes also show more complex wavefront distortions, collectively known as *higher-order aberrations* (HOAs). The existence of these higher-order refractive defects has been known for years, but only in recent times have we developed practical devices to measure them and, in some cases, to correct them. This is a story closely tied to the development of advanced astronomical instrumentation. In the lab, eye aberrations are now measured — and even compensated for — using essentially the same kind of wavefront sensors, deformable mirrors, and laser guide stars that are used in today's high-resolution adaptive-optics systems.

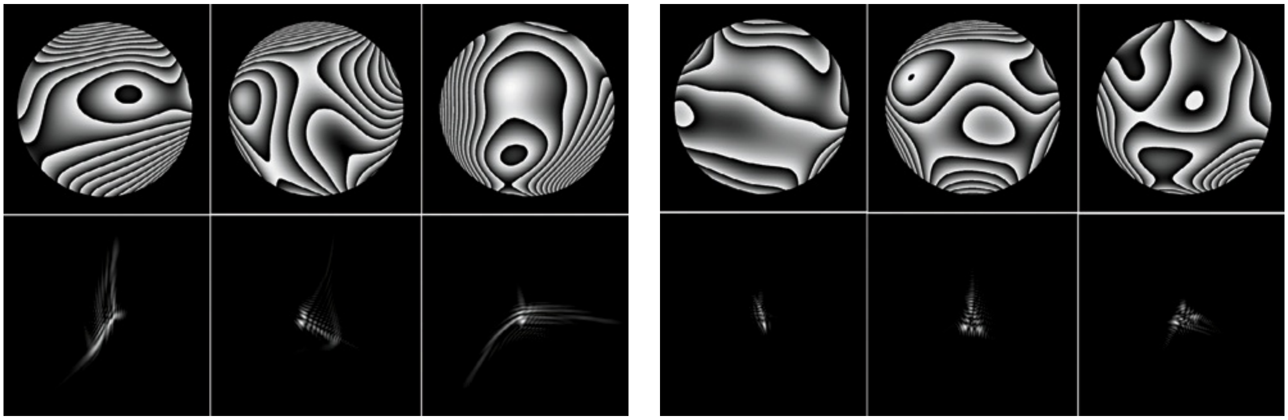
So are we fighting a losing battle against our eyes? Not at all. A better understanding of your own eyes' strengths and weaknesses can actually improve your observing.

Play With Pupil Sizes

Each human eye has its own aberration pattern. This pattern creates unique "star images" on the retina. Under normal nighttime viewing conditions and with fully dilated pupils, the retinal image of a bright point source may span several tens of arcminutes and can be even greater than the angular size of the full Moon. This irregularly shaped light distribution is commonly called the eye's *point-spread function* (PSF). The aberrations might be similar in a person's left and right eye, but patterns vary widely between people. Aberrations are in some sense the eye's fingerprints.

The magnitude of aberrations increases with pupil diameter and with age. Once spectacles or other equipment corrects for the classical forms such as myopia, the HOAs of healthy eyes for people in their 30s are still typically far more severe than you would accept in your telescope optics.

When observing extended objects such as the Moon or planetary nebulae, your eye aberrations will blur the target's small-scale structures. The magnitude of this blurring is highly variable between people, but it averages what would be produced by the lowest increment in a prescription for myopia, 0.25 diopter. That's not too much for everyday life, but it will be noticeable for any careful visual astronomer.



***Left panels*: Eye-aberration maps of the right eyes of three observers (*top row*) and how a point source looks to their retinas (*bottom row*). The pupil diameter is 6.5 mm, and the size of each retinal image box is 36.5 arcminutes, slightly bigger than the full Moon. The maps are like topographic plots: the grayscale between consecutive curves spans 0.5 micrometer in height, like terrain elevations — except here the "terrain" is the difference between the ideal and actual wavefronts. If no aberrations existed, the maps would be completely flat. *Right panels*: Eye-aberration maps and retinal images of a point source for the same observers in the left panel, but with fully corrected second-order aberrations (that is, showing only the higher-order effects).**

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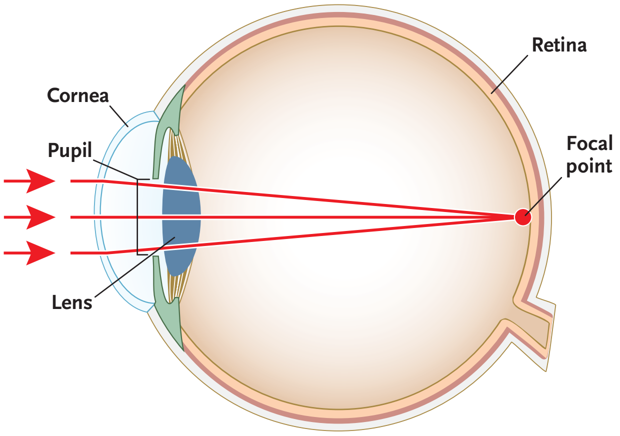

In an ideal eye, light (red rays) passing through the eye's lens should focus on the retina at the back of the eye. However, few of us have eyes that meet this standard. *S&T* ILLUSTRATION: CASEY REED

The eye's resolution improves at first with decreasing pupil diameter, because shrinking the pupil size also shrinks the halo created around a point source by the eye's aberrations. But for very small pupil diameters of about 1 mm or less, diffraction limits the resolution. (A 1-mm aperture, for example, has a fundamental resolution limit of about 2 arcminutes.) As a result, eyes tend to perform best with pupil diameters in the 2–3 mm range (a typical daytime pupil size).

For visual observing through a telescope, the effective pupil size will be determined by your instrument's "exit pupil" or by the entrance pupil of your eye, whichever is smaller. Using eyepieces with small exit pupils is a good strategy to stop down the aperture and counteract the effects of your eye aberrations. Small exit pupils may also be helpful if your eyes have a moderate to high astigmatism and you prefer to not wear spectacles when observing: unlike near- and farsightedness, you cannot fully compensate for astigmatisms (or HOAs) by simply refocusing the telescope.

The size of your telescope's exit pupil is given by the diameter of the telescope's objective divided by the magnification. You may find that for your particular telescope (and eyes) there is a range of magnifications that give you the most detailed images. For example, if your optimum pupil diameter is about 2 mm and the aperture of your telescope is 200 mm, then magnifications close to 100× will probably do the best job. When observing objects at lower magnifications (and hence using eyepieces that create larger exit pupils), you may want to stop down the exit pupil by putting an appropriately sized hole in a spare eyepiece cap and putting the cap on the eyepiece. The aperture stop should ideally sit at the plane of the exit pupil, the precise position of which will depend on your eyepiece's eye relief. You can also stop down the telescope objective itself by using a set of masks with diameters appropriate for your most frequently used magnifications.

Of course, retinal image resolution is not the only issue when selecting an eyepiece. When it comes to observing the delicate structure of dim, extended objects, the target's average brightness and size also come into play. It's easier to detect small contrasts in images that are


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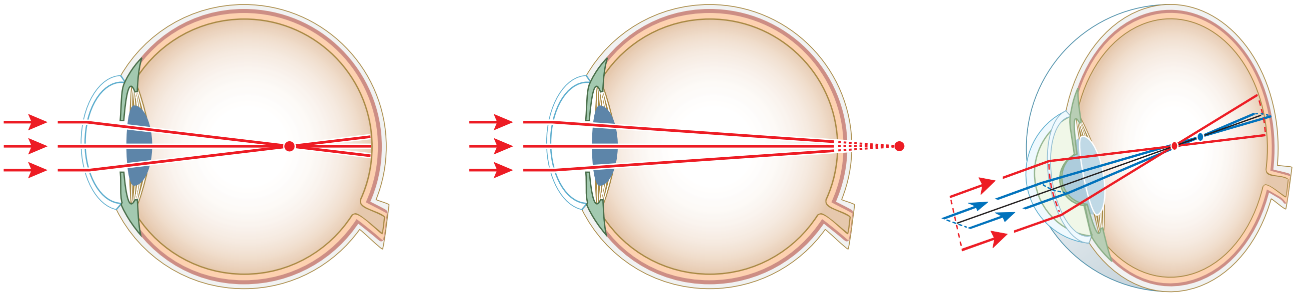
Looking at Your Eyes' Aberrations

If you wish to observe how irregularly your eye distributes light, look at a bright pointlike source surrounded by a dark background while wearing your usual prescription glasses or contact lenses. Since the central core of the eye's light distribution, or *point-spread function* (PSF), is generally much brighter than the wings, you need a dark background in order to observe the subtle structure of these peripheral regions. Keep the ambient light level low to encourage your pupils to dilate. With dilated pupils, ocular aberration effects will become more noticeable. Suitable pointlike sources are bright celestial objects, such as Sirius or Jupiter; unshielded streetlamps a few hundred meters away; or even tiny LEDs at the other end of a darkened room.

Look at the light sources with each eye separately, covering the unused eye with your hand or a card (closing your eye can affect the result), and let your brain perceive the retinal images. You may find that the PSFs of your right and left eyes look a bit symmetric. Then look with both eyes — you will probably perceive a pattern composed of your eyes' individual results.

You can also look through tiny holes of different sizes in a piece of cardboard in order to determine the best diameter for your vision. Also shift the hole side-to-side to find the position that gives the best image: the optical quality of the eye stopped by an artificial aperture is *not* homogeneous across the pupil, and some pupil regions provide better overall optical quality than others.

***Left column*: The spread of an eye's light distribution for different pupil diameters, from 6 mm (top) to 1 mm (bottom), decreasing in steps of 1 mm. *Right column*: the light distribution for an ideal eye with no aberrations, for the same pupil sizes.**



bright and big, but bright images call for low magnifications, whereas big images require high ones. You'll need to compromise in order to simultaneously achieve enough brightness and magnification while keeping aberration blur at bay. In these cases, the optimum pupil size might be somewhat different from that suggested by eye aberrations alone.

Aberrations Made Normal

Our visual system has its own ways of compensating for its limitations. One phenomenon, known as the Stiles-Crawford effect, reduces the perceived brightness of light rays entering pupils' outer edges in comparison with the rays entering the pupil center. Peripheral rays are generally the most affected by aberrations, but most photoreceptor cells point toward the pupil's center, naturally minimizing the problem. Another correction, suggested by a recent experiment carried out by the teams of Pablo Artal (University of Murcia, Spain) and David Williams (Center for Visual Science, University of Rochester), happens when the brain simply adapts to its particular eye-aberration pattern, removing part of the aberration-induced blur.

Several technologies can optically compensate for the eye's aberrations, mostly at the research laboratory level. But researchers are also studying whether normal eye aberrations are actually helpful for vision: recent studies show that they may well be the eye's defense against chromatic blur. If so, they would not be mere defects.

Nevertheless, besides bad atmospheric conditions, your eye aberrations can be one of the main sources of poor resolution in visual observing, especially when you're using relatively large-aperture instruments at low magnifications, with their resulting large exit pupils. Should we then give back our eyes? Probably not. Helmholtz himself added a wise (and seldom-quoted) qualification to his dismay:

> Of course, I shall not do this with my eyes, and shall be only too glad to keep them as long as I can — defects and all.

Surely most of us would agree with him.

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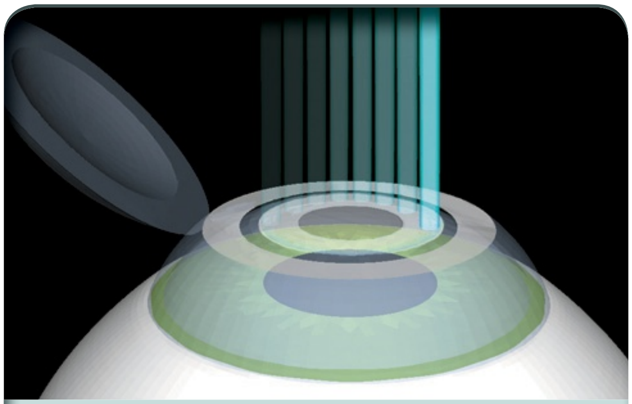
Second-order aberrations move the eye's focal point forward (nearsightedness, *left*), backward (farsightedness, *center*), or create two perpendicular foci, depending on the plane in which light rays travel (astigmatism, *right*). The eye can also have more complex distortions, which further affect focusing. *S&T* ILLUSTRATIONS: CASEY REED (3)



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Will LASIK help?

LASIK refractive surgery is an efficient technique to correct the classic aberrations called *ametropies* — nearsightedness, farsightedness, and astigmatism — by laser removal of corneal tissue (*S&T*: September 2005, page 36). Advanced surgical systems have wavefront sensors that allow surgeons to attempt to correct not only these ametropies but also several higher-order aberrations (HOAs). However, the practical results of LASIK concerning HOAs still fall somewhat short of expectations. Although the ametropy correction is highly successful and patients are usually very happy with the overall outcome, their post-surgical HOAs tend to increase by a factor of about two. Surgical systems and procedures are getting more precise as time goes by, and it is foreseeable that in the near future these outcomes will improve. Meanwhile, if you are planning to undergo refractive surgery and eye aberrations are an issue for you, talk about them openly with your surgeon so you can make an informed decision.