Supernormal Vision

A focus on adaptive optics improves images of the eye and boosts vision

By CORINNA WU

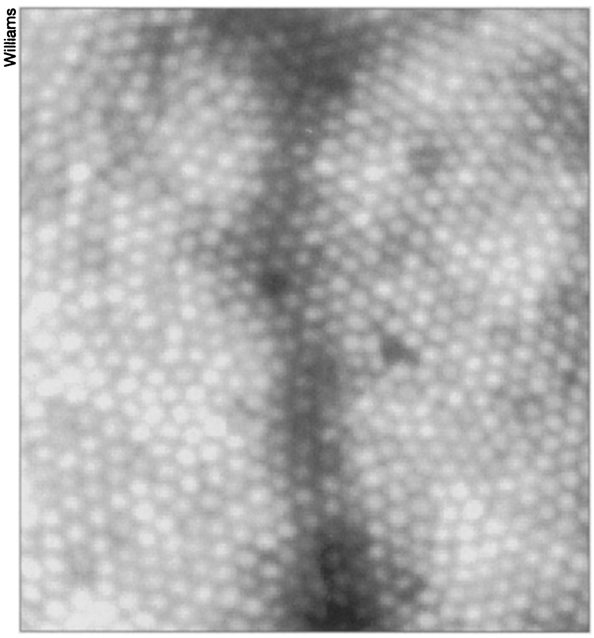
Anyone who grew up reading comic books may recall the advertisements that always graced the back pages, touting weird and wonderful gizmos designed to appeal to fun-loving youngsters. In one classic ad, a crew-cut boy sporting horn-rimmed "X-ray specs" stares gleefully at the bones in his hand. With the specs, the ad promised, mere mortals could acquire the super-vision of Superman.

Most people with failing eyesight are satisfied just to have glasses or contact lenses that can keep their vision within the 20/20 range. One group of researchers, however, has developed a technology that can endow people with a new kind of supernormal vision. Following the tradition of binoculars' helping people to observe distant objects and night vision goggles' allowing them to see in the dark, the most recent technology enables the human eye to detect finer detail than is ordinarily possible.

At a seminar sponsored by Research to Prevent Blindness and held in Los Angeles in September, vision scientist David R. Williams of the University of Rochester in New York explained the approach that he and his group have taken. They have embraced the technique of adaptive optics, originally designed to sharpen images from military surveillance devices and astronomical telescopes. As applied to the human eye, the system allows people to see at high resolution, but it also works in reverse, allowing researchers to capture extraordinarily detailed images of the eye's retina.

That, in fact, is the group's main goal. Clear, detailed images of the retina could improve the diagnosis, understanding, and treatment of diseases such as glaucoma and age-related macular degeneration, both of which can cause blindness. As part of their adaptive optics system, Williams and his group also have adopted a new way of measuring the eye's imperfections that could help to improve the performance of contact lenses and allow more accurate assessment of corrective eye surgery.

Williams and his colleagues recently obtained the clearest pictures yet of individual cells in the retina, an achievement that Howard C. Howland of Cornell University calls "spectacular." The retina acts as the eye's movie screen, receiving a projected image of the ever-changing world. Light entering the eye hits not a white, reflective surface, but a carpet of rods and cones—two kinds of photoreceptor cells that serve different purposes. Rods detect dim light and are needed for peripheral vision, while cones function in bright light and are responsible for color vision. Cone cells come in red, blue, and green types, the names indicating their color sensitivities.



Williams

A high-resolution image of a living human retina reveals a mosaic of photoreceptor cells.

"Spatial arrangement and relative numbers [of rods and cones] are not well characterized in the human retina," says Williams. So far, most studies have been done in excised eyes, not in living people, Howland adds. To take a picture of the intact retina, a researcher has to send a flash of light into the eye, then record the light that bounces off the retina with a camera.

The same imperfections in the eye's cornea and lens that reduce visual acuity, however, also warp retinal images obtained in this way, limiting their resolution. "If you had a perfect eye, the light would come out parallel," says Williams, and could be focused into an undistorted image of the retina.

Many common vision problems, such as myopia and astigmatism, are caused by aberrations in the shape of the eye that are easy to correct with eyeglass lenses. Other aberrations are harder to deal with, both in improving a person's vision and in examining the eye.

Several years ago, the Rochester group found a solution for dealing with such troublesome distortions when they examine eyes: They do a trick with mirrors. The researchers can direct the light leaving an eye onto a deformable mirror—the key to adaptive optics—and correct for any aberration, thereby producing the highest quality images of the retina ever seen (SN: 10/8/94, p. 231).

A deformable mirror or perhaps contact lenses designed with an adaptive optics system could also improve a person's vision by compensating for such aberrations, the researchers suggest.

Adaptive optics got its start in the 1970s, when the U.S. military was looking for ways to obtain clear photographs of Soviet satellites. The turbulence of the atmosphere blurs images to such an extent that even digital enhancement can't improve them. Later, as part of the Strategic Defense Initiative, popularly known as the Star Wars program, the military studied adaptive optics as a way to compensate for atmospheric distortions when focusing a ground-based laser weapon on an incoming missile.

Eventually, the technology found its way into astronomy, where it can overcome the atmospherically induced twinkling and blurring that afflict images of stars (SN: 6/8/91, p. 358). A few years ago, Williams and his coworker Junzhong Liang paid a visit to Robert Q. Fugate at the Starfire Optical Range at Kirtland Air Force Base near Albuquerque to learn about adaptive optics for their own vision research. Fugate pioneered the astronomical use of the technique.

The basic strategy in adaptive optics is to collect light waves with a deformable mirror whose shape can be adjusted to compensate for distortions in an image. In photographing a retina, Williams uses a flexible mirror with 37 pistons on the back that can change the shape of the reflecting surface. Because the wavelength of light is less than 1 micrometer, the pistons don't need to move more than about 3 micrometers.

The researchers coupled the mirror to a special high-resolution camera and took images of the retina both when the mirror was flat and when it was adjusted. The adjusted mirror, which corrected for the distortions produced by imperfections in the eye, gave clear, detailed pictures.

"It's the first time you can resolve single cone cells in the retina," says Williams. "The images are twice as good as before." By increasing the number of pistons, the group may be able to eliminate even more subtle imperfections and further improve the images.

Howland, whose own work focuses on measuring eye aberrations, says that the technique "holds enormous promise. David Williams has achieved a real triumph for imaging the retina." Liang, Williams, and their colleague Donald T. Miller report their findings in the November JOURNAL OF THE OPTICAL SOCIETY OF AMERICA A.

In addition to revealing the structure of the retina, high-quality pictures could provide a way for doctors to detect diseases earlier, Howland says. For example, glaucoma damage can be detected only after prolonged destruction of the retina's nerve fiber layer. The technique could also enable doctors to chart more precisely the retinal blood vessel damage resulting from diabetes and other diseases.

For adaptive optics to work successfully, the pistons must deform the mirror into just the right shape. To calculate what that shape should be, the system must first measure the aberrations in the eye. Before coming to Rochester, Liang and his colleagues at the University of Heidelberg in Germany adapted for this purpose a device called the Hartmann-Shack wavefront sensor.

First, a laser beam shines into the eye and reflects off the retina. The reflected light, having passed through the cornea and lens, emerges from the pupil and splits into 217 individual beams. "It comes out [as if from] the compound eye of an insect," says Williams. Finally, an electronic device detects the array of beams and maps each one's location.

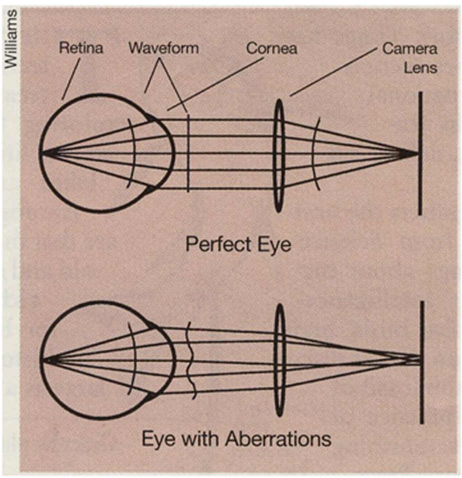
"If the eye were perfect, then the 217 beams would be spaced regularly," Williams says. "If not, they're warped."

Measuring the displacement of each spot provides a snapshot of the eye's aberration. Only 40 or 50 beams are needed to get a good characterization, says Williams, but the group records all 217. A computer transforms these measurements into a prescription for adjusting the pistons so that the mirror precisely compensates for the eye's imperfections.

There are other ways to measure aberrations, Howland says. He uses a device called an aberroscope, which projects a grid onto the retina. He photographs the grid and analyzes the twisted, wavy lines created by the cornea's imperfections. What a person sees in this test is analogous to looking through a mesh screen at a distant street light, he says.

Accurate measurements of eye aberrations by such methods could pave the way for better contact lenses, Williams says. "My dream is someday to sculpt a contact lens into just the right shape." Howland cautions that some of the subtler aberrations are very difficult to correct for, however, and that contact lenses alone may not do the trick.

Measurement techniques could also improve surgical procedures now used to correct vision, which often introduce new aberrations while correcting the natural ones. In radial keratotomy for myopia, for example, a doctor slices the cornea around the pupil in pizza-cutter fashion to flatten the cornea. This procedure is "the worst [type of eye surgery] in terms of introducing spherical aberration," says Howland. Afterwards, the patient may see clearly in bright light, when the pupil is small, but have less acute vision at night, when the pupil is enlarged. Currently, corrective surgery can't be tailored precisely to an individual eye, in part because of the difficulty of accurately measuring aberrations.



To take an image of the retina, researchers send a 4-millisecond flash of light into the eyeball and record the reflected light. Before emerging from the pupil, the waveforms of light are smooth in both perfect eyes and eyes with aberrations.

In a perfect eye (top), the light rays shining out of the pupil are undistorted and parallel. A camera lens focuses the rays onto a piece of film, reproducing the sharp point of light.

In an eye with aberrations (bottom), the light rays are not perfectly parallel after passing through the imperfect cornea and lens and therefore do not focus in one spot. The result is a blurred image.

Researchers expect to benefit from an improved ability to peer into a patient's eyes, but some people with normal vision are interested in using adaptive optics to enhance their ability to see the world.

Experiments conducted by Williams' group show that adaptive optics can indeed give people better visual acuity. "Subjectively, when you look through the [adaptive optics] device, the world looks sharper," Williams says. In tests of adaptive optics, people have experienced up to a sixfold improvement in their sensitivity to contrast, seeing fine stripe patterns that were indistinguishable to the naked eye.

In fact, the system improves resolution so well that the retina's mosaic arrangement of photoreceptors ultimately gets in the way, Williams says. For example, when volunteers looked at tiny points of red light that had a wavelength of 633 nanometers, the color sometimes appeared green—depending on which type of cone cell the beam happened to hit. The perceived color of an object normally arises from the stimulation of a large patch of cone cells, but in the experiment, the point of light seemed to fluctuate between colors. Williams notes that improving vision in one way may degrade it in others.

The adaptive optics system could serve as a useful tool in exploring theories of how the structure of the eye limits vision. Some researchers have argued that the human eye has an image quality superior to what one would expect from the patchwork of rods and cones in the retina. Since adaptive optics can get rid of all eye aberrations—leaving only the retina to limit resolution—researchers can put this theory to the test.

Even though adaptive optics has the potential to make human eyes sharper than an eagle's, the immediate applications focus on preventing vision loss and correcting everyday eyesight problems. The technology, however, may encourage those who never got their X-ray specs to again dream of becoming bionic women and men. □