Simple tricks of vision

(Editor's note: Take time out from technical papers and Society news for "The light touch," a fresh Optics & Photonics News column meant to be shared with students and children of all ages.)

We take the human eye for granted, but it is a remarkably powerful and sophisticated optical system. The array of optical sensors that form the retina are connected to a pattern recognition system far more powerful than the fastest supercomputer—the vision center of the human brain. The eye and the brain together give us an extremely detailed picture of the world, compensating smoothly for some of their own limitations. However, a few simple experiments can reveal some of the eye's limits.

Specialized nerve cells in the retina respond to light and transmit signals to the brain. There are two similar types: cones and rods. The roughly seven million cones respond to bright light and sense color. The 125 million rods respond to dim light, but do not sense color. The rods are so sensitive to light that they are essentially bleached out in sunlight and do not respond at all. However, they recover their sensitivity after you turn off the lights.

It takes a minute or two for your eyes to start to "dark adapt" as the rods turn on, to sense light much too faint for the cones. If you go outside on a dark night, you will see faint stars gradually come into view as your eyes dark adapt. It takes about half an hour for your eyes to become fully dark adapted, but the change is most obvious in the first few minutes outside. If you live in a brightly lit urban area, scattered light from street lamps, car headlights, houses, and signs makes the sky so bright that your eyes never fully dark adapt. You will never see colors at night, because the rods lack color receptors.

The differences between rods and cones, and the different patterns they make on the retina, have some interesting consequences that we don't often notice. The cones respond to all the colors in the visible spectrum, from 400 to 700 nanometers. However, the cones are not sensitive to wavelengths longer than 600 nm, so red objects seem darker at night than in bright light.

Many cones are packed tightly together near the center of the retina, a point called the "fovea," where the lens of the eye focuses light from objects straight ahead. Because they are tightly packed, the cones near the fovea have the highest resolution in the

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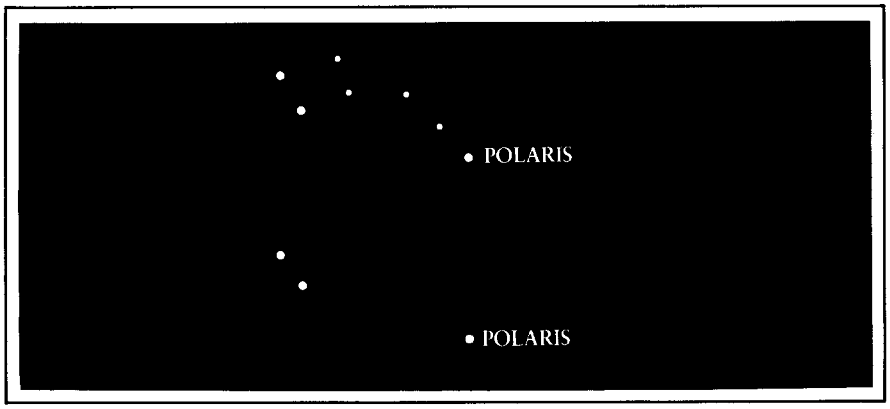


FIGURE 1. The faint stars in the middle of the Little Dipper are easier to see (above) if you look directly at Polaris instead. Try to look directly at the stars in the Little Dipper and they may disappear (below) because your eyes are focusing their light on the less-sensitive cones at the center of the eye.

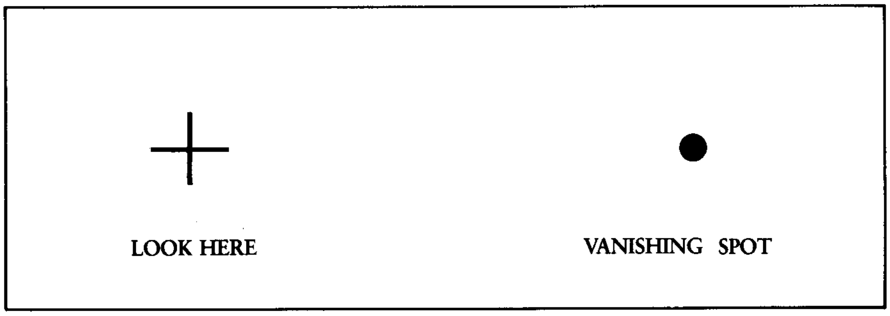


FIGURE 2. Close your left eye and focus your right eye on the cross. Move the page back and forth and the circle will vanish when it falls on your blind spot. (From Jeff Hecht, Optics: Light for a New Age, Charles Scribner's Sons, New York, 1988.)

JEFF HECHT is a contributing editor to *Optics & Photonics News* and *Lasers & Optronics*. He is the author of *Optics—Light for a New Age*.

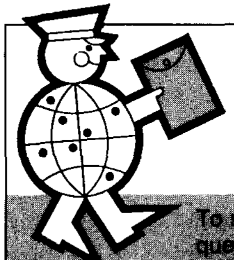
LIGHT TOUCH, *from page 55*

eye, giving us our detail vision. When we read, our eyes focus light onto the fovea and the surrounding area—the "macula"—so we can see the detail needed to make sense of the words. Some elderly people suffer a condition called "senile macular degeneration," which impairs their detail vision, leaving them unable to read books set in normal size type.

The tight concentration of cones near the fovea leaves no room for rods, so there are none near the center of vision. Most of the 125 million rods are on the sides of the retina. This means that at night you see poorly in the area where you direct your eyes, the same area where you can see best during the day. This makes seeing in the dark difficult, because we are so used to being in the light that we automatically turn our eyes toward what we want to see.

Amateur astronomers are well aware of this effect, and use a technique called "averted vision" to better view faint objects in the dark night sky. If they want to see a dim star, they focus their eyes on a nearby bright star. The dim star then appears off to the side. If their eyes wander toward the dim star, it may seem to vanish—because its light is focused onto the fovea, where there are no cones to respond to it. The best way to see averted vision work is by looking directly at a fairly bright star. You will see other, fainter, stars nearby, but those fainter stars will disappear if you try to focus on them. This works well with Polaris and the fainter stars of the Little Dipper, if your sky is not too bright, as shown in Fig. 1.

Rods and cones are not distributed symmetrically around the eye. They are absent altogether from one small area near the back of the eye, where the optic nerve connects with the retina. Normally, our brain conceals this blind spot by using information from our other eye. However, you can demonstrate its existence by closing your left eye and focusing your right eye on the cross in Fig. 2. Move the page back and forth, and at some point the circle will fall on your blind spot and vanish.



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THE LIGHT TOUCH

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. Though 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.

The power of compound eyes

The compound eye of an insect is made up of many separate visual units (Figure 1). In this article, we discuss the power of the compound eye.

It is clear that the eye of an insect is able to detect the movement of an enemy or prey, as well as patterns of light and dark areas. But this equipment would not seem to give an insect a clear, sharply defined image of the external world. Of course, we do not know that what we see is any more real than what insects see. The signals conveyed to our brains produce certain instinctive reflex actions—we may turn away or close our eyes. By more complicated mental processes, visual memory influences visual perceptions. Insects react by visual memory: for example, returning to a nest and using visual landmarks.

When we compare ourselves to insects, we find a way in which our vision is incomplete. Insects see about the same amount of the red end of the spectrum as we do, but they see much further into the ultraviolet. Insects avoid the light, *e.g.*, when offered a spectrum of colors that includes infrared and ultraviolet, ants carrying their pupae into shelter will avoid all of our visible spectrum and a space beyond it, choosing as "dark" places the infrared and ultraviolet. In precise terms, their general range is from 2,500Å to 7,000Å, compared with the human range of 4,000Å to 7,000Å.

This color range of insects has largely determined the hues of meadows and forest, for varieties of flowers that appealed to insect pollinators had the best chance of survival through the ages of evolution. Few bee-pollinated flowers are solid red, for to the bee red looks the way black does to the human eye. There are numerous blue and violet, yellow and yellowish-green flowers that fall within the range of the bee's color vision. In addition, there are a number of blossoms that appear muted to the human eye, but glow with ultraviolet magnificence for bees.

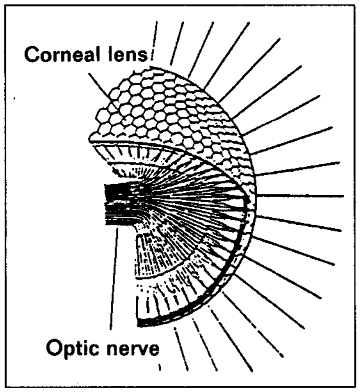

Figure 1. The compound insect eye consists of many tiny individual eyes, each connected to its own nerve endings. The eye as a whole does not move, nor can its lenses be focused. Each catches a small piece of the surrounding scene and the result is a rather coarse-grained picture, like a mosaic.

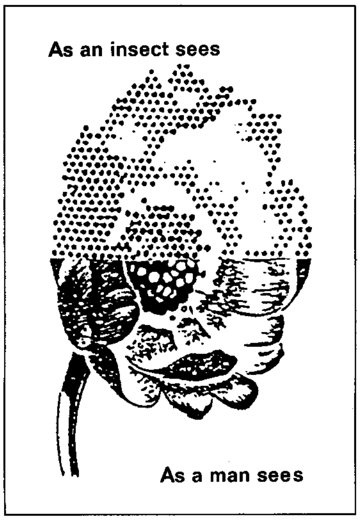

Figure 2.

Insects' ability to get their bearings from sunlight partly depends on polarization, which is generally invisible to man. For the insect, there is a different quality of light coming from north, east, south and west at different hours of the day. As a consequence, insects need only to see the sky to navigate. More remarkable, honeybees can tell where the sun is even in a cloudy sky. This is because a certain amount of ultraviolet light penetrates the clouds and the sun's part of the sky is always about 5% brighter in the ultraviolet than the rest. This difference is enough for the bees to pinpoint the sun on the cloudiest day.

Putting things in perspective

A facet is a part of the cornea, a transparent area of the cuticle. Beneath this may be a crystalline cone, a hard refractive body, which in combination with the facet of the cornea forms a real image of what ever lies in front of it (Figure 2). Some dragon flies are said to have nearly 30,000 facets in each eye, which makes sense because they

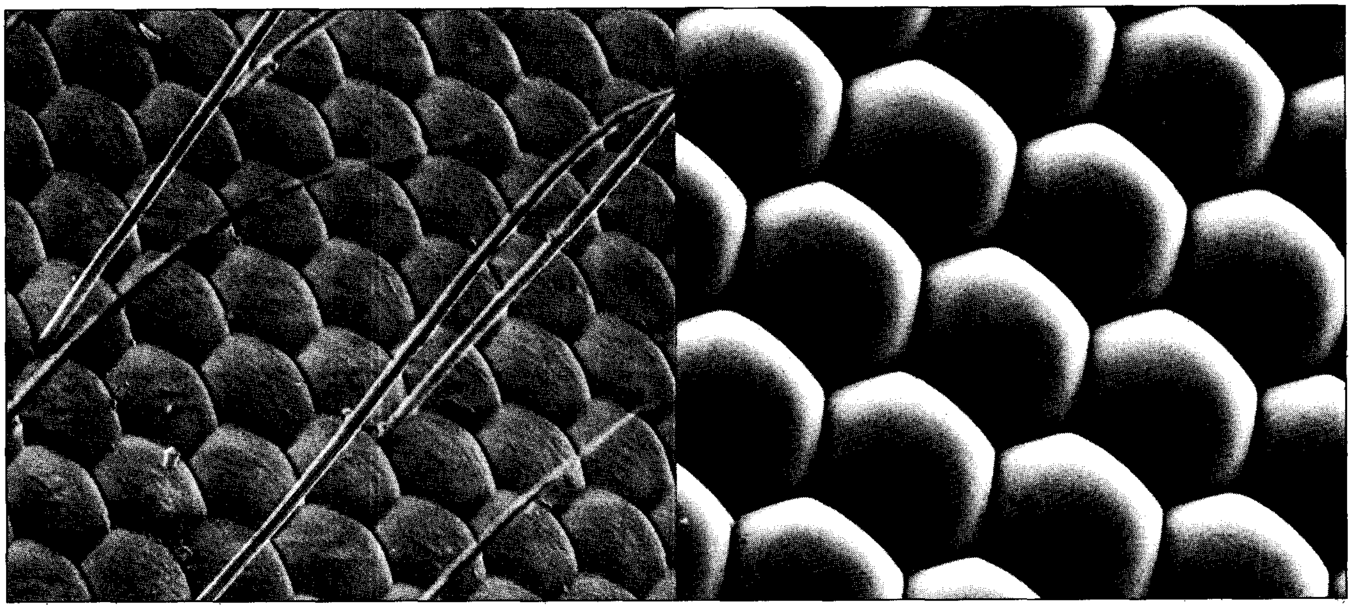

Figure 3. Scanning electron picture of a moth eye (3a) and a house-fly eye (3b) taken on an 840A JEOL microscope.

hunt in flight. Butterflies and moths, which do not hunt in flight, only have 12,000 to 17,000 facets (Figure 3a). The true house-fly must be content with only 4,000 facets (Figure 3b).

Insects cannot close their eyes; they rest with them open. Their vision is believed to be sharp only to a distance of 2 to 3 feet (51 to 91 cm). Insect eyes have no way of focusing to achieve a sharper image; they depend on an increase in the number of individual mini-eyes for an increase of sharpness much as a printer relies on a fine halftone screen to print the tiny dots that make up a sharper picture with a wealth of detail.

The familiar lens of glass that we use in cameras, microscopes, and the like, is made from material with a uniform refractive index. The bending of light rays to form an image is then determined by the curvature of the various surfaces and the distance between them. The cornea and the crystalline cone of the insect eye is a laminated structure, made like the layers of an onion. The refractive index is greatest along the axis and least toward the sides. As a device for bringing light rays to a focus, the lens-cylinders system of the insect eye is thus more complicated than that of the simple lenses made by man.

* * *

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Auto-random-dot stereograms

We perceive depth in our normal vision because our brain stereoscopically combines the two slightly different views from our horizontally separated eyes. Although there are other (monocular) depth cues such as shading and perspective, humans are particularly receptive to this binocular disparity. In fact, picture pairs (or stereograms) can induce stereopsis when they are contrived binocular disparity.

Typical stereograms, such as 3-D movies, contain several monocular depth cues because each component image forms a realistic, two-dimensional scene when viewed separately. Conversely, random-dot stereograms combine two seemingly random black-and-white patterns of dots, which, when viewed stereoscopically, produce a three-dimensional figure solely on the basis of binocular disparity.[1] Because of the lack of several interacting depth cues, it may take several minutes for the observer to recognize depth from the random-dot patterns, while it only takes milliseconds to perceive ordinary stereograms.

While most stereograms require special viewing equipment, such as polarized glasses or color filters, the auto-random-dot stereogram[2] in Figure 1 works by free viewing. In this case, you must only focus your eyes correctly on a single pattern of "random" dots to perceive a three-dimensional scene. You may have already experienced a simple version of this type of stereopsis if you've ever looked at a repetitively tiled floor and had the disconcerting sensation of seeing the tiles floating above your feet.

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To view the auto-random-dot stereogram in Figure 1, focus your eyes on the page while holding a pencil between the stereogram and your eyes. You should see two misfocused pencil images. Move the pencil to align the blurred images with the two fixation markers—the heavy black dots—on the stereogram. Then, without moving your eyes, focus on the pencil. The two blurred pencils should converge into one sharp image that points at the central spot of three blurred markers. Continue focusing on the pencil until the central spot sharpens in focus. (This may take seconds or minutes.) When this happens, you should begin to see the raised checkerboard pattern.

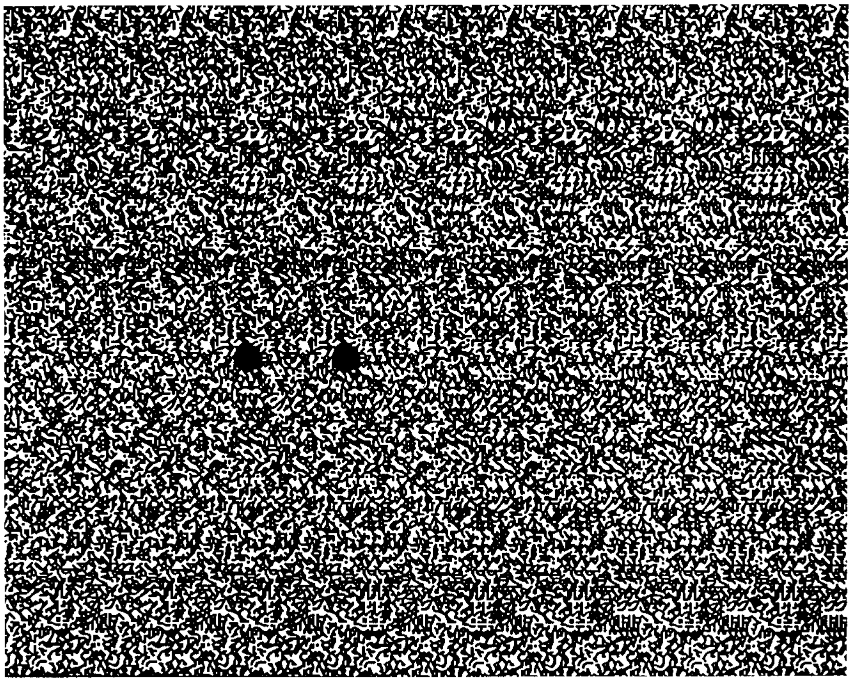

Figure 1. A raised checkerboard pattern appears from this auto-random-dot stereogram. Viewing instructions are given in the text.

The fixation markers are separated by the convergence distance. This distance is the amount by which the image in the left eye is shifted from the image seen by the right eye. As you saw in trying to view the stereogram, each eye sees both markers, but they are shifted horizontally such that only the right marker in the left eye's image overlaps the left marker in the right eye's image. Thus, you saw three markers at correct convergence. In fact, each eye sees its own view of the entire stereogram shifted with respect to the other by the convergence distance. These two views correspond to the two sides of a stereo pair. However, unlike a standard stereogram, both views are identical, so the single dot pattern itself contains the depth discontinuity information.

Depth is encoded into the stereogram by assigning a nearly random pattern of black-and-white dots to each row of the stereogram array with a length corresponding to the convergence distance. This pattern repeats itself along the row until a depth discontinuity is encountered. The pattern is interrupted by a number of dots

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Crosstalk—from page 7

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Engineering—from page 52

manufacturing environment. Restoring American competitiveness requires putting increased emphasis on high quality efficient manufacturing methods.

- Engineering problems are rarely as "clean" as a course's homework problem set. Advanced courses should involve engineering trade-offs, including the ambiguities that usually accompany real engineering tasks.
- Participation in cooperative education programs and development of summer student internship programs must be encouraged and expanded.

Education—from page 53

week and was consequently more intensive. Future workshops, following the 1990 format, will likely be held every two years beginning in 1992. Proceeding of the 1990 workshop was videotaped and copies are available. For further details, please contact the authors.

Acknowledgements

CHTM is an interdisciplinary organization with a central mission to support research, advanced study, and technology transfer in optics and optoelectronics. Overall management of both workshops was handled by John G. McInerney and Steven R.J. Brueck, with assistance from Vivienne H. Mattox of Management Plus Inc. The authors are grateful to her and to the technical and administrative staffs of the Center for High Technology Materials for extensive logistical support before and during each workshop. We acknowledge financial support from the National Science Foundation through contract numbers USE-8854282 and USE-8954342. Finally, we thank all the workshop alumni for their enthusiastic participation and follow-up.

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proportional to the perceived height of the discontinuity. A new pattern arises from the remaining dots that continues until the next depth discontinuity is reached. Following this recipe, crude stereograms can be made using a typewriter. The more sophisticated stereogram in Figure 1 was produced by David G. Stork at Stanford University using a Macintosh computer. Using his program,[3] a typical stereogram containing 18,000 dots takes only a few minutes to create. According to Stork, future auto-random-dot stereograms will use gray levels and color to enhance the 3-D effect.

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Abstract deadlines

March 4: OSA Coherent Laser Radar Topical Meeting, July 8-12, Snowmass, Colo.

March 15: OSA Photorefractive Materials, Effects and Devices Topical Meeting, July 29-31, Beverly, Mass.

March 28: OSA Nonlinear Guided Wave Phenomena Topical Meeting, Sept. 2-4, Cambridge, UK

April 5: Optical Amplifiers and their Applications Topical Meeting, July 24-26, IEEE-LEOS/OSA, Snowmass, Colo.

May 1: OSA Persistent Spectral Hole-Burning Science and Applications Topical Meeting, Sept. 26-28, Monterey, Calif.

Light touch

The blue arcs: An electrifying visual phenomena

Editor's note: Take time out for "The light touch," an OPN column meant to be shared with students and children of all ages.

The proliferation of red LEDs on electronic equipment of every sort has made it easy to observe one of the more interesting entoptic phenomena. Normally, visual experiences are caused when light stimulates the retina, the network of nerve cells at the back of the eye. Entoptic phenomenon are produced when something other than light stimulates the retina. Thus, if you gently poke the side of the eye with your lids closed, you will see a spot of light on the opposite side of the visual field. This so-called pressure phosphene is caused by mechanical stimulation of nerve cells.

A wide variety of interesting effects are produced when an electric current is run through the eye, but this is not generally recommended as a casual demonstration. However, there is one effect of electrical stimulation that can be seen in complete safety. For this you need to find one of those red LEDs (try your camera's flash unit, your stereo system, VCR, etc). When you have an LED, look at it in a dark room with one eye. If you use your right eye, you should see one or two blue arcs emerging from the light source and ending somewhere to the right. The arcs will go in the opposite direction in the left eye. If you move your eyes so that the red light falls in different spots in the visual field, you will see the arcs move and change,

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Jeremy M. Wolfe, associate professor, Department of Brain and Cognitive Sciences, Program in Psychology, MIT.

Figure 1 **The blind spot**

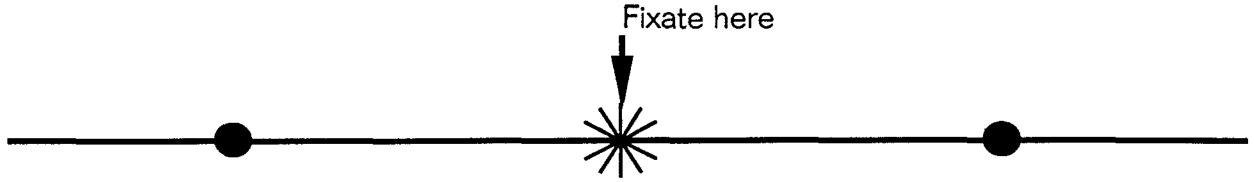

Figure 2 **The wiring of the retina**