The Undeniable Case for Global Warming (*see page 64*)

SCIENTIFIC AMERICAN

Hungry Shark's
ELECTRIC SENSE
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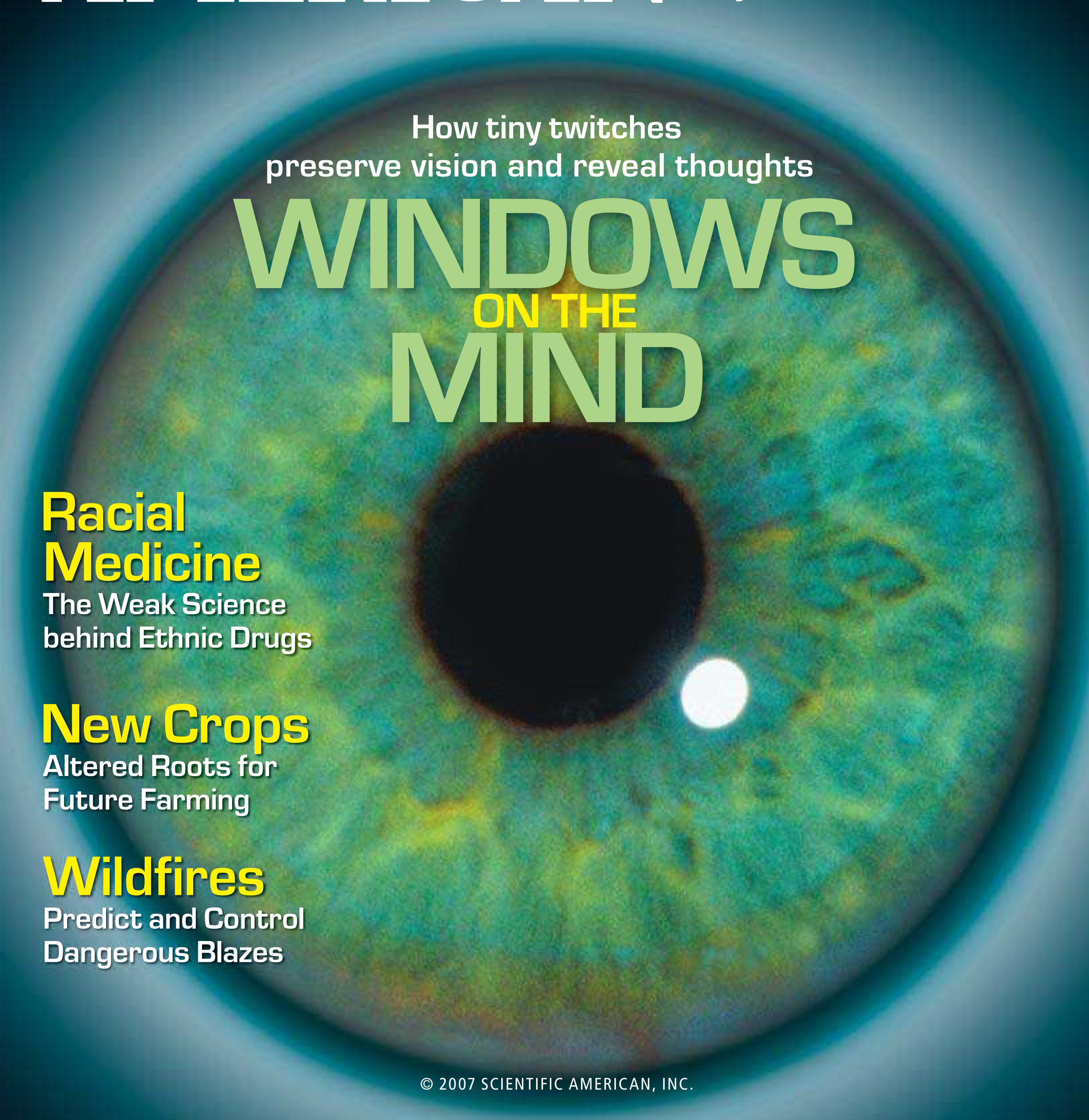

How tiny twitches preserve vision and reveal thoughts

WINDOWS ON THE MIND

Racial Medicine
The Weak Science behind Ethnic Drugs

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Predict and Control Dangerous Blazes

Once scorned as nervous tics, certain tiny, unconscious flicks of the eyes now turn out to underpin much of our ability to see. These movements may even reveal subliminal thoughts

By Susana Martinez-Conde and Stephen L. Macknik

Windows on the

As you read this, your eyes are rapidly flicking from left to right in small hops, bringing each word sequentially into focus. When you stare at a person's face, your eyes will similarly dart here and there, resting momentarily on one eye, the other eye, nose, mouth and other features. With a little introspection, you can detect this frequent flexing of your eye muscles as you scan a page, face or scene.

But these large voluntary eye movements, called saccades, turn out to be just a small part of the daily workout your eye muscles get. Your eyes *never* stop moving, even when they are apparently settled, say, on a person's nose or a sailboat bobbing on the horizon. When the eyes fixate on something, as they do for 80 percent of your waking hours, they still jump and jiggle imperceptibly in ways that turn out to be essential for seeing. If you could somehow halt these miniature motions while fixing your gaze, a static scene would simply fade from view.

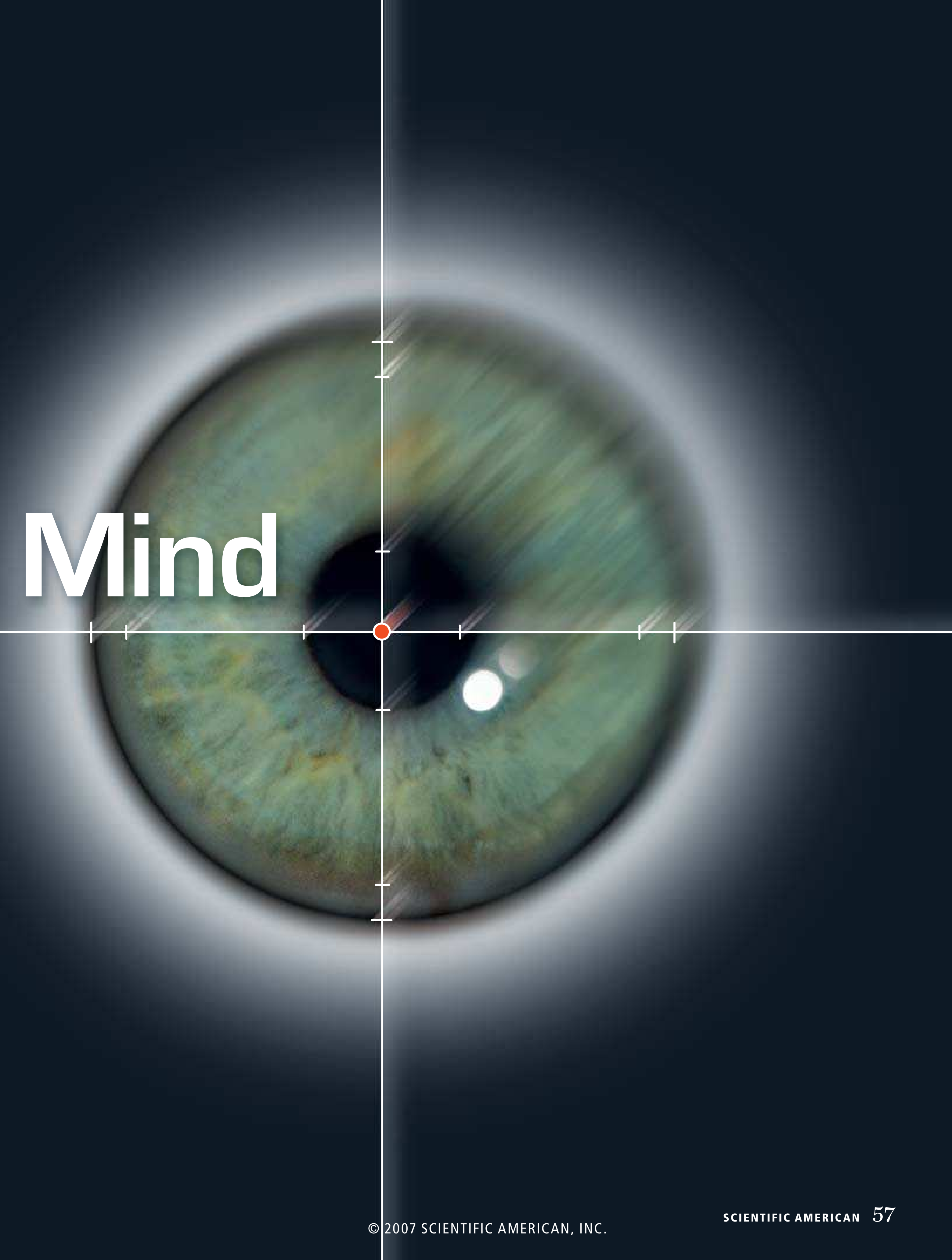
And yet only recently have researchers come to appreciate the profound importance of such "fixational" eye movements. For five decades, a debate has raged about whether the largest of these involuntary movements, the so-called microsaccades, serve any purpose at all. Some sci-

KEY CONCEPTS

- When the eyes fix on something, they still jump imperceptibly in ways that turn out to be essential for seeing.
- For decades, scientists have debated the purpose, if any, of these so-called fixational eye movements, the largest of which are called microsaccades. Now the authors have demonstrated that microsaccades engender visibility when a person's gaze is fixed and that bigger and faster microsaccades work best.
- Microsaccades may also shed light on subliminal thoughts. Recent research suggests that the direction of microsaccades is biased toward objects to which people are unconsciously attracted, no matter where they are actually looking.

—The Editors

JENS NIETH *zefa/Corbis (photograph)*; JEN CHRISTIANSEN *(photoillustration)*


Mind

> Tiny subconscious eye movements are helping neuroscientists crack the brain's code for conscious visual perceptions.

entists have opined that microsaccades might even impair eyesight by blurring it. But recent work in the laboratory of one of us (Martinez-Conde) at the Barrow Neurological Institute in Phoenix has made the strongest case yet that these minuscule ocular meanderings separate vision from blindness when a person looks out at a stationary world.

Meanwhile microsaccades are also helping neuroscientists crack the brain's code for creating conscious perceptions of the visual world. In the past few years, we and others have detected telltale patterns of neural activity that correlate with these little movements, which we now believe drive most of what people perceive. What is more, microsaccades may form a window into your mind. Instead of being random, these little ocular shifts may point to where your mind is secretly focusing—even if your gaze is directed elsewhere—revealing hidden thoughts and desires.

Fatigued by Sameness

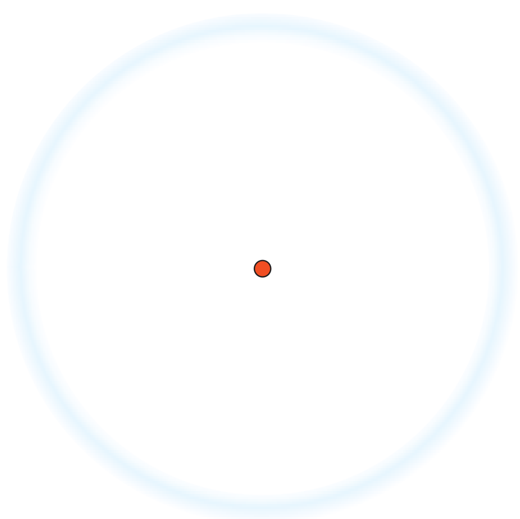
That the eyes move constantly has been known for centuries. For example, in 1860 German doctor and physicist Hermann von Helmholtz pointed out that keeping one's eyes motionless was a difficult proposition and suggested that "wandering of the gaze" prevented the retina, several layers of cells at the back of the eye, from becoming tired.

Indeed, animal nervous systems have evolved to detect changes in the environment, because spotting differences promotes survival. Motion in the visual field may indicate that a predator is approaching or that prey is escaping. Such changes prompt visual neurons to respond with electrochemical impulses. Unchanging objects do not generally pose a threat, so animal brains—and visual systems—did not evolve to notice them. Frogs are an extreme case. A fly sitting still on the wall is invisible to a frog, as are all static objects. But once the fly is aloft, the frog will immediately detect it and capture it with its tongue.

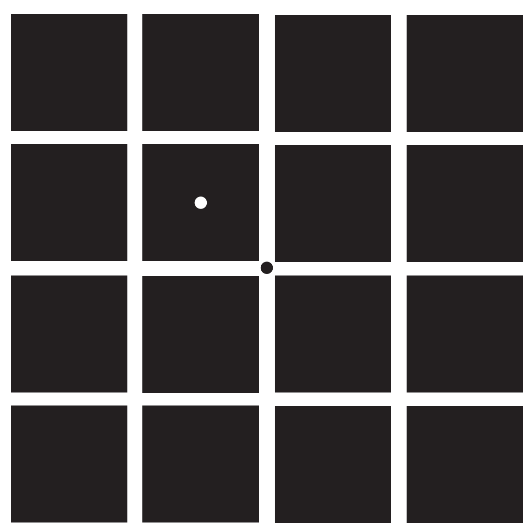
Frogs cannot see unmoving objects because, as Helmholtz hypothesized, an unchanging stimulus leads to neural adaptation, in which visual neurons adjust their output such that they gradually stop responding. Neural adaptation

MINIATURE EYE MOVEMENTS REVEALED

With these three illusions, you can observe various visual effects of your fixational eye movements, which are typically beneath your awareness.



TROXLER TEST: In 1804 Swiss philosopher Ignaz Paul Vital Troxler discovered that deliberately focusing on something causes surrounding stationary images to fade away. To elicit this experience, stare at the red spot while paying attention to the pale blue circle. The circle soon vanishes, and the red spot appears set against a white background. Move your eyes, and it pops back into view.



SEEING THE EYES MOVE: Here is a way to "see" your fixational eye movements. Look at the central black dot for about a minute, then look at the white dot in the adjacent dark square. Notice that the dark afterimage of the white cross-hatching is in constant motion. That is a result of your fixational eye movements.

SOURCES: IGNAZ PAUL VITAL TROXLER (*left*); "A SIMPLE AFTER IMAGE METHOD DEMONSTRATING THE INVOLUNTARY MULTIDIRECTIONAL EYE MOVEMENTS DURING FIXATION," BY F. J. VERHEIJEN, IN *JOURNAL OF MODERN OPTICS*, VOL. 8, NO. 4, PAGES 309–312; OCTOBER 1961; © TAYLOR AND FRANCIS LTD. (*right*) saves energy but also limits sensory perception. Human neurons also adapt to sameness. But the human visual system does much better than a frog's at detecting unmoving objects, because human eyes create their own motion. Fixational eye movements shift the entire visual scene across the retina, prodding visual neurons into action and counteracting neural adaptation. They thus prevent stationary objects from fading away.

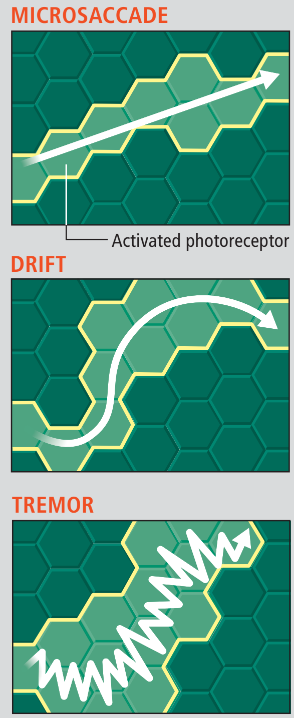
In 1804 Swiss philosopher Ignaz Paul Vital Troxler reported the first fading phenomenon in humans related to a decrease in fixational eye movements. Troxler noted that deliberately focusing on something causes stationary images in the surrounding region to gradually fade away [*see left illustration in box on opposite page*]. This fading happens to you every day, because deliberately focusing on something can briefly slow or reduce fixational eye movements, which are also less effective outside your area of focus. Thus, even a small reduction in the rate and size of your eye movements greatly impairs your vision. You do not notice the impairment, because you are not paying attention to invisible portions of your view, focusing on what is directly in front of you instead.

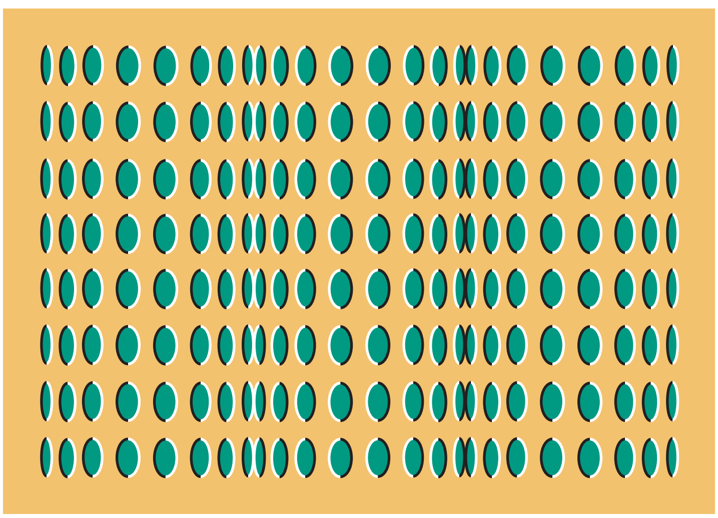
Totally ceasing all eye movements, however, can only be done in a laboratory. In the early 1950s some research teams achieved this stilling effect by mounting a tiny slide projector onto a contact lens and affixing the lens to a person's eye with a suction device. In this setup, a subject views the projected image through this lens, which moves with the eye. Using such a retinal stabilization technique, the image remains still with respect to the eye, causing the visual neurons to adapt and the image to fade away. Nowadays researchers create this same result by measuring the eye's movements with a camera pointed at it. They transmit the eye-position data to a projection system that moves the image with the eye.

In the late 1950s researchers were able to isolate a role for microsaccades: after suppressing all eye movements in the lab, including the larger voluntary saccades, they superimposed microsaccadelike motions and found that doing so restored perception. Other research teams, however, found otherwise: adding back

MOVING TARGETS

Fixational eye movements, including microsaccades (straight lines), drifts (wavy lines) and tremor (zigzags superimposed on drifts), transport the visual image over a mosaic of photoreceptors on the retina.



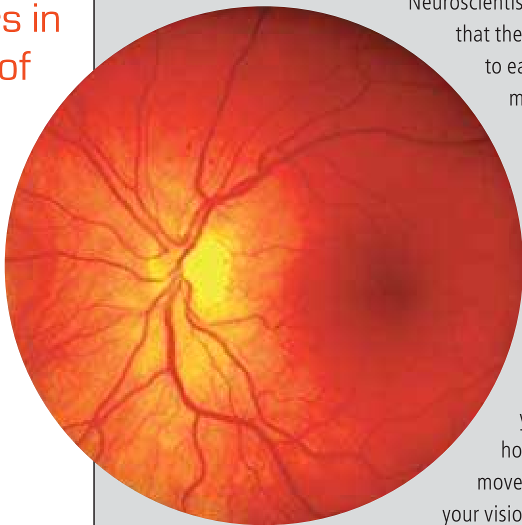


ILLUSORY MOTION: Let your eyes wander around the pattern above, and the three "rollers" will appear to spin. But if you hold your gaze steady on one of the green spots in the center of the image, the illusory motion will slow down or even stop. Because holding the eyes still stops the illusory motion, the authors speculate that the fixational eye movements may be required to see it, although they do not yet know exactly how.

Microsaccades elicit neuronal rejoinders in every part of the visual system we have examined.

[DO-IT-YOURSELF]

VANISHING VESSELS



Neuroscientists David Coppola and Dale Purves of Duke University showed that the blood vessels in the retina, which are stationary with respect to each eye, can fade from a person's view in a mere 80 milliseconds (thousandths of a second). You can see this for yourself. Close your eyes while lightly holding a small flashlight (not too bright!) up to the side of one of your eyes. If you move the flashlight around rapidly, you might catch a glimpse of your retinal blood vessels in your peripheral vision. But notice how quickly they fade from view.

Neural adaptation takes place in all of the senses, including touch. For instance, you may feel your shoes when you first put them on in the morning, but the feeling goes away after a while. You probably do not want to be aware of your shoes 16 hours a day, after all. If you wiggle your toes, however, you can feel your shoes again. Similarly, fixational eye movements constantly "wiggle" the images on the retina so that your vision never goes away. *—S.M.-C. and S.L.M.*

microsaccades after freezing eye movements had no effect at all in these experiments. The truth was hard to discern because none of the techniques for stabilizing the retina was perfect; for instance, a contact lens attached to the eye can slip, leaving some residual eye movements. In the end, no one could tell whether an experimental result was caused by those residual movements or the superimposed microsaccades.

Nervous Tics?

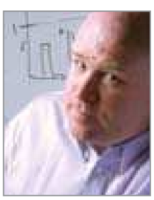
Around the same time, investigators identified two other flavors of fixational eye movements: drifts and tremor. Drifts are slow, meandering motions that occur between the fast, linear microsaccades. Tremor is a tiny, rapid oscillation superimposed on drifts. Microsaccades are the largest of the fixational eye movements, carrying an image across dozens to several hundred of the eye's photoreceptor (light-detecting) cells, including cones for detail and color vision and rods for low-light and peripheral vision. Tremor is the smallest of the fixational eye movements, its motion no bigger than the size of one of these cells. We do not yet understand the relative roles of these various fixational eye movements in vision, however.

In fact, for decades, many vision scientists doubted whether any of these fixational eye movements—especially microsaccades, which were the most studied—had a role in maintaining vision. Critics noted that some individuals could suppress microsaccades for a couple of seconds without their central vision fading away. (You can see this in the Troxler test; as you briefly suppress your microsaccades, the ring fades, but you can still see the red dot in the center of your view.) And people naturally hold microsaccades at bay momentarily when they perform precision tasks such as shooting a rifle or threading a needle. In 1980 University of Maryland psychologists Eileen Kowler and Robert M. Steinman concluded that microsaccades were useless, supposing that they might be "merely a kind of nervous tic."

There the field stood until the late 1990s, when researchers began to investigate which neuronal responses, if any, fixational eye movements might be generating in the eye and brain. Starting in 1997, along with Nobel laureate David Hubel of Harvard Medical School, we trained monkeys to fixate on a small spot presented on a computer monitor, which also displayed a stationary bar of light elsewhere on the screen. As the monkeys stared, we recorded their eye movements and the electrical activity from neurons in the lateral geniculate nucleus (LGN) in their midbrain and in the primary visual cortex at the back of their brain [*see box on opposite page*]. In each experiment the bar was placed in a location that would elicit an optimal electrical response—in the form of impulses called spikes—from the recorded neurons.

The results of these experiments, published in 2000 and 2002, showed that microsaccades increased the rate of neural impulses generated by both LGN and visual cortex neurons by ush-

[THE AUTHORS]



Susana Martinez-Conde is director of the Laboratory of Visual Neuroscience at the Barrow Neurological Institute in Phoenix. She holds a Ph.D. in medicine and surgery from the University of Santiago de Compostela in Spain. **Stephen L. Macknik** is director of the Laboratory of Behavioral Neurophysiology at the Barrow Neurological Institute and earned a Ph.D. in neurobiology from Harvard University.

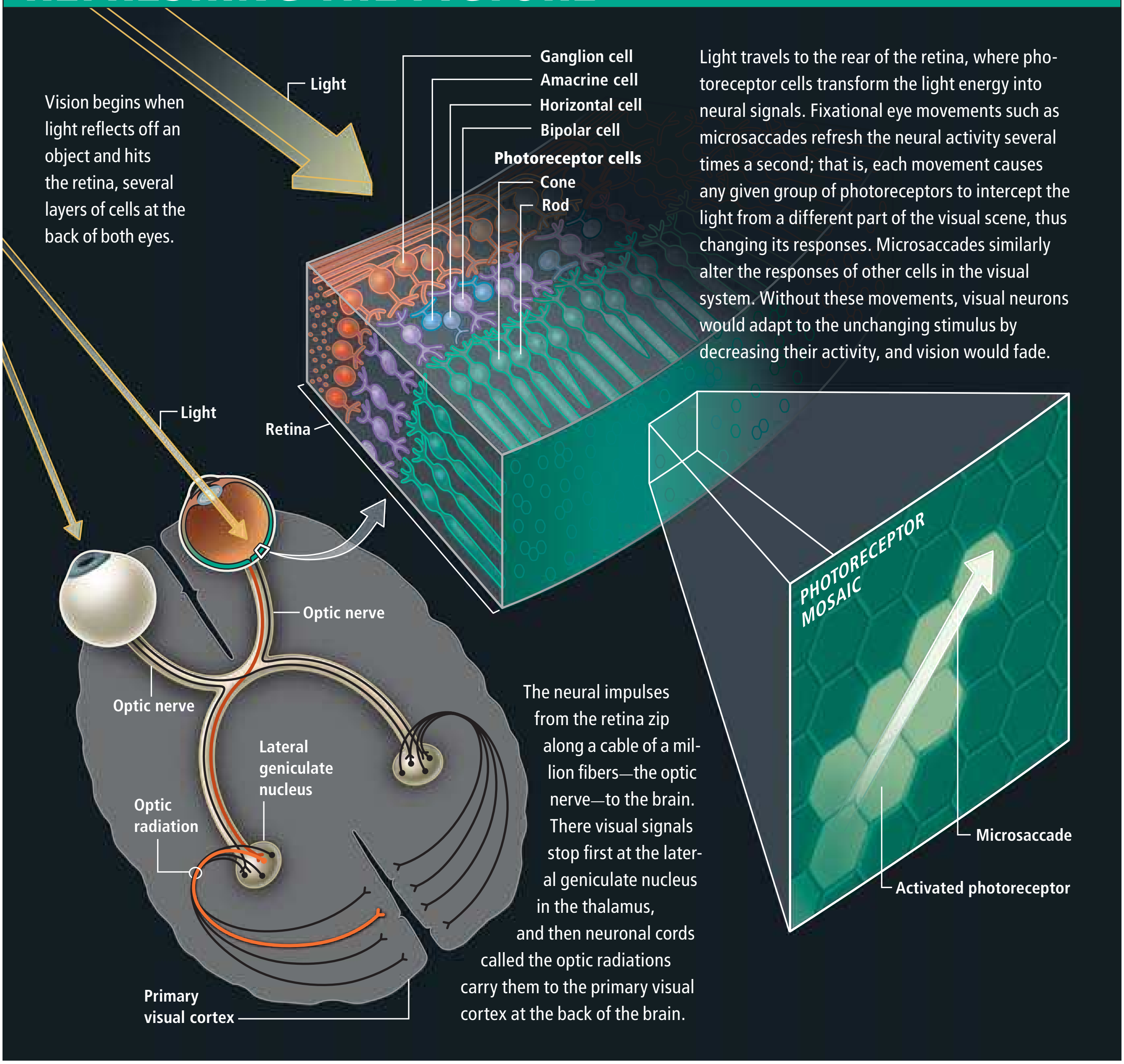
STEVE ALLEN *Brand X/Corbis (top)*; JEFF NOBLE *(Martinez-Conde and Macknik)* ering stationary stimuli, such as the bar of light, in and out of a neuron's receptive field, the region of visual space that activates it. This finding bolstered the case that microsaccades have an important role in preventing visual fading and maintaining a visible image. And assuming such a role for microsaccades, our neuronal studies of microsaccades also began to crack the visual system's code for visibility. In our monkey studies we found that microsaccades were more closely associated with rapid bursts of spikes than single spikes from brain neurons, suggesting that bursts of spikes are a signal in the brain that something is visible.

Cracking the Case

Other researchers also found that microsaccades elicit neuronal rejoinders in every part of the visual system that they examined. Nevertheless, the field was still haunted by the conflicting results in the retinal stabilization experiments, casting lingering doubt over the importance of microsaccades in vision. So a few years ago, at the Barrow Neurological Institute, we

[THE BASICS]

REFRESHING THE PICTURE



JEN CHRISTIANSEN

You may avert your eyes from that last piece of cake or an attractive man or woman near you, but the rate and direction of your microsaccades betray your true focus.

set out to directly measure the relation between microsaccades and visibility using a completely different technique. In our experiments, we asked volunteers to perform a version of Troxler's fading task. Our subjects were to fixate on a small spot while pressing or releasing a button to indicate whether they could see a static peripheral target. The target would vanish and then reappear as each subject naturally fixated more—and then less—at specific times during the course of the experiment. During the task, we measured each person's fixational eye movements with a high-precision video system.

As we had predicted, the subjects' microsaccades became sparser, smaller and slower just before the target vanished, indicating that a lack of microsaccades—or unusually small and slow microsaccades—leads to adaptation and fading. Also consistent with our hypothesis, microsaccades became more numerous, larger and faster right before the peripheral target reappeared. These results, published in 2006, demonstrated for the first time that microsaccades engender visibility when subjects try to fix their gaze on an image and that bigger and faster microsaccades work best for this purpose. And because the eyes are fixating—resting between the larger, voluntary saccades—the vast majority of the time, microsaccades are critical for most visual perception.

Such work is not just of theoretical import but might also have therapeutic implications. That is, a better understanding of the importance of fixational eye movements in vision may provide insights into diseases and conditions that impair these movements. For instance, a lack of fixational eye movements can result from paralysis of the oculomotor nerves, which control most of the eye movements. Abnormal fixational eye movements are also common in amblyopia, or "lazy eye," a loss of detail vision without any detectable pathology and the leading cause of vision loss in one eye among 20- to 70-year-olds. In severe amblyopia, excessive drift and too few microsaccades can cause objects and even large portions of the visual scene to fade away during fixation.

In normal vision the oculomotor system must achieve a delicate balance between too few fixational eye movements and too many, which lead to blurred and unstable vision during periods of fixation. Understanding how that eye-motion system achieves such a balance might one day enable doctors to recalibrate the system when something goes awry. A large number of disorders impact fixational eye movements, making this a fertile research field that so far remains largely unexplored.

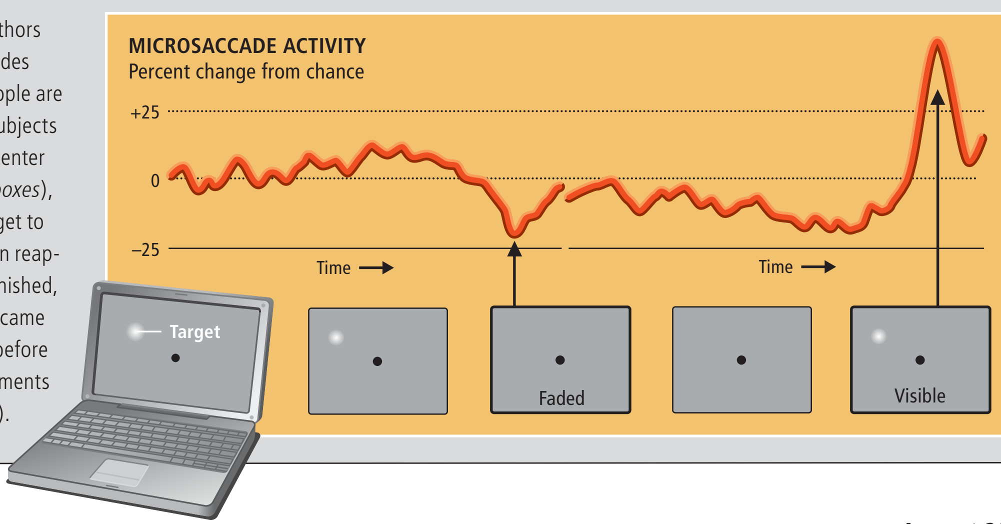
Reading the Mind

Microsaccades may have significance beyond vision. These little eye movements may also help expose a person's subliminal thoughts. Even when your gaze is fixed, your attention can unconsciously shift about a visual scene to objects that attract your interest, psychologists have found. Recent research suggests that microsaccades can reveal such objects of attraction because the direction of microsaccades, instead of being totally random, may point right to them—even if you are looking elsewhere.

Vision scientists Ziad M. Hafed and James J. Clark of McGill University asked volunteers

SEEING WITH MICROSACCADES

In a recent experiment, the authors demonstrated that microsaccades bring about visibility when people are fixing their gaze. They asked subjects to stare at a small spot in the center of a computer screen (*row of boxes*), causing a static peripheral target to vanish from their view and then reappear. Just before the target vanished, the viewers' microsaccades became sparser and slower, and right before it reappeared, these eye movements became more frequent (*graph*).



JEN CHRISTIANSEN

BRIAN MARANAN PINEDA

ATTENTION MONITOR: **Scientists can track microsaccades to determine if something is secretly attracting a person's attention—such as a slice of chocolate cake—even when that person is looking elsewhere. But don't worry. Ordinary people cannot easily use these eye movements to read your mind.**

to direct their eyes to a central spot on a computer monitor while paying attention to a peripheral spot that changed color at the end of each trial. The volunteers were supposed to indicate this color change. In 2002 Hafed and Clark reported that the direction of the subjects' microsaccades was biased toward their true point of focus, even though they were looking elsewhere. This finding indicated not only that microsaccades may point to people's covert thoughts but also, the authors noted, that covert shifts of attention actually control the direction of microsaccades.

In another experiment, computational neuroscientist Ralf Engbert and cognitive psychologist Reinhold Kliegl of the University of Potsdam in Germany found that the *frequency* of microsaccades also conveys the presence of something that secretly attracts a person's attention. The abrupt appearance of a visual cue in the periphery of a person's field of view, they stated in 2003, causes first a brief drop in the rate of microsaccades, followed by a rapid rebound in which microsaccade frequency exceeds normal. Furthermore, the microsaccades they detected were biased in the direction of the cue. The study suggests that microsaccade frequency and direction can signal sudden changes in the environment that attract a person's attention when he or she does not look directly at them.

Thus, no matter how hard you might avert your eyes from the last piece of cake on the table or the attractive male or female standing across the room, the rate and direction of your microsaccades betray your attentional spotlight. This betrayal is not a practical concern, however. In the laboratory, scientists can detect and measure these minuscule eye movements to reveal the hidden brain mechanisms of attention, but people around you cannot easily use them to read your mind—yet. ■

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➥ MORE TO EXPLORE

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Akiyoshi Kitaoka's illusion pages: www.ritsumei.ac.jp/~akitaoka/index-e.html

Martinez-Conde Laboratory: www.neuralcorrelate.com/smc_lab