GANDEE VASAN *Getty Images*

Tiny subconscious eye movements called microsaccades stave off blindness in all of us—and can even betray our hidden desires

SHIFTING FOCUS

By Susana Martinez-Conde and Stephen L. Macknik

Look up from this page and scan the scene in front of you. Your eyes dart around, bringing different objects into view. As you read this article, your eyes jump to bring every word into focus. You can become aware of, and even control, these large movements of the eyes, which scientists call saccades. But even when your eyes are apparently fixed on something—say, on a tree, face or word—they are moving imperceptibly, underneath your awareness. And recent research shows that these minute, subconscious eye movements are essential for seeing.

If you could somehow halt these miniature motions, any image you were staring at would fade from view. In fact, you would be

Adapting to Sameness

At one time in your life, you may have scoured your house or apartment in search of your glasses, only to realize that you were wearing them. When you first put on your glasses, the touch receptors in the skin of your face and head gave you a rich sensory impression of their location, weight and tightness. But since then, you have not felt their presence. The reason is neural adaptation, in which neurons gradually decrease their output in response to an unchanging stimulus. Neural adaptation is a critical and ubiquitous process in the nervous system. It takes place in all the senses—vision as well as touch. Try to touch the elastic band of your sock without looking, while you keep your legs and feet still. If you missed it by at least a couple of inches, blame neural adaptation. After all, that band has not moved in a while. Your ability to see static objects would go away, too, if fixational eye movements did not constantly "wiggle" the images on your retina. *—S.M.-C. and S.L.M.*

rendered blind for most of the day. Although these eye movements have long baffled scientists, only recently have researchers come to appreciate their importance. Indeed, we now have garnered strong evidence that the largest of these involuntary meanderings, the so-called microsaccades, are critical to everyday vision.

Microsaccades are also providing new clues to neurological ailments that affect both eyesight and movement. Even more intriguingly, they can serve as a window into your mind. These seemingly random ocular shifts are not arbitrary after all: they can point to where your mind is secretly focusing—even if your gaze is aimed elsewhere—revealing hidden thoughts and desires.

FAST FACTS

Eyes in Action

1» **Even when you think your eyes are staring, fixed in space, they are actually on the go. Their miniature motions prevent you from being blind to most of what is out there.**

2» **Tiny "fixational" eye movements also support our ability to search a visual scene, in concert with the bigger shifts of our eyes of which we are often consciously aware.**

3» **Minute flicks of the eyes called microsaccades can reveal objects that attract our attention.**

Sleepy Stares

Researchers have known for centuries that the eyes move all the time. For example, in 1860 German doctor and physicist Hermann von Helmholtz suggested that "wandering of the gaze" prevented the retina, several layers of cells at the back of the eye, from becoming tired.

Movement near you may indicate that a predator is approaching or that prey is getting away. Animal nervous systems have evolved to detect such changes, which prompt visual neurons to emit electrochemical impulses. Because unchanging objects do not generally pose a threat, some animals are blind to unmoving objects; recall the *T. rex* in *Jurassic Park*. A fly sitting still on the wall is invisible to a frog, for example, but as soon as the fly is aloft, the frog can capture it with its tongue. Neuroscientist Jerome Lettvin of the Massachusetts Institute of Technology and his colleagues stated in their classic 1959 paper, "What the Frog's Eye Tells the Frog's Brain," that frogs "will starve to death surrounded by food if it is not moving."

TERRY VINE *Alamy (woman)*; ALAMY *(frog)*

As Helmholtz correctly proposed, an unchanging stimulus causes neurons to gradually stop responding to the input,

Minute movements shift the visual scene across the eyes, waking up neurons and preventing stationary objects from fading away.

a phenomenon known as neural adaptation [*see box on opposite page*]. Neural adaptation saves energy by reducing the metabolism in neurons that do not receive new information, but it also limits what we can perceive. Although human visual neurons can adapt to unchanging stimuli, our visual system copes with lack of change better than a frog's because human eyes create their own motion even when we fix our gaze. Fixational eye movements—which include drifts and tremor as well as microsaccades [*see box on next page*]—shift the entire visual scene across the retina, prodding visual neurons into action and preventing stationary objects from fading away.

In 1804 Swiss philosopher Ignaz Paul Vital Troxler was the first to report that deliberately focusing on something can make unmoving images in the surrounding region gradually fade away [*see box on this page*]. You experience this disappearing act every day because a purposeful stare can briefly reduce fixational eye movements. Because you are training your eyes on whatever is directly in front of you, you do not notice the problem.

In the late 1950s researchers first pinpointed a perceptual role for microsaccades: after suppressing all eye movements to stabilize images on the retina for extended periods, they superimposed microsaccadelike motions and found that doing so brought back normal eyesight. (For a description of the original way images were stabilized, see page 53.) Other research teams, however, struggled to duplicate the results. For decades, many vision scientists even doubted whether microsaccades had a part in maintaining and restoring vision.

Shaken Awake

Then, in the late 1990s, researchers tried another approach. They began to investigate which neuronal responses, if any, microsaccades might be generating in the brain. Starting in 1997, along with Nobel laureate David H. Hubel of Harvard Medical School, we trained monkeys to stare at a small spot on a computer monitor, which also displayed a bar of light elsewhere on the screen. As the monkeys stared, we recorded their eye movements and the electrical activity from neurons in two visual brain areas: the lateral geniculate nucleus, a relay station between the retina and visual areas of the brain, and the primary visual cortex at the back of the brain [*see box on page 55*]. These experiments, published in 2000 and 2002, showed that microsaccades increased the rate of impulses from neurons in both visual regions. They do so by moving stationary stimuli, such as the bar of light, in and out of the region of visual space that activates a given neuron. Microsaccades essentially help to refresh an image to prevent it from fading. Other researchers documented similar effects in other parts of the visual system.

A few years ago we set out to link microsaccades with visibility using a different technique. In a version of Troxler's fading task, we asked people to fixate on a small spot and release a button when they saw a black-and-white patch in their peripheral vision. They pressed the button when the patch disappeared. The patch would vanish and then reappear as each person naturally fixated more—and then less—as they performed the task. Meanwhile we measured his or her eye movements using a high-precision video apparatus.

The Vanishing Ring

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 gray circle. The circle soon vanishes, and the red spot appears set against a white background. Move your eyes, and it pops back into view.

FROM "THE ROLE OF FIXATIONAL EYE MOVEMENTS IN VISUAL PERCEPTION," BY SUSANA MARTINEZ-CONDE, STEPHEN L. MACKNIK AND DAVID H. HUBEL, IN *NATURE REVIEWS NEUROSCIENCE*, VOL. 5; MARCH 2004

Beyond their role in our ability to see, microsaccades may reveal some of what we are thinking.

The subjects' microsaccades became less frequent and smaller just before the target vanished, showing that fewer microsaccades—or very small ones—lead to fading. In addition, microsaccades became more numerous and larger right before the target reappeared. The results, published in 2006, proved that these minute jumps counteract the visual fading of stationary objects and that bigger microsaccades produce the best visibility. And because our eyes are fixating—resting between saccades—more than three quarters of the time, microsaccades may be essential to our ability to see much of the time we are awake.

Where's Waldo?

As with saccades, microsaccades may also be involved in searching for something in a scene. Along with our colleagues at the Barrow Neurological Institute, we asked participants to look at pictures from Martin Handford's book *Where's Waldo?* and report to us when they succeeded in finding Waldo. At the same time, we recorded their eye movements. We found that the frequency of microsaccades was highest when people spotted Waldo. The results, published in 2008, revealed a direct link between microsaccades and how we search a scene.

We further determined, whether they were hunting for Waldo, exploring visually at will, or solving *Life* picture puzzles, that people tended to produce recurring saccades or microsaccades about 200 milliseconds apart. Because these different types of eye movements occur at similar intervals yet not simultaneously, we thought that the same neural structure might generate both. Complimentary experiments by vision scientist Martin Rolfs and his colleagues at the University of Potsdam in Germany led them to propose that the superior colliculus, a brain area directly responsible for orienting the eyes and head toward objects in the environment, might trigger both saccades and microsaccades.

This hypothesis received strong neurophysiological support in 2009. The superior colliculus is arranged in a map of visual space so that activity in the caudal (rear) portion produces large saccades in specific directions away from the center of gaze, whereas activity in the rostral (frontal) portion drives small saccades to eye positions near the center of gaze. Neuroscientists Ziad M. Hafed and Richard J. Krauzlis, then at the Salk Institute for Biological Studies, and Laurent Goffart of the Mediterranean Institute for Cognitive Neuroscience in Marseille, France, recorded impulses from individual neurons in the rostral part of the superior colliculus and found that they also triggered microsaccades. After the researchers blocked the output of this part of the brain with drugs, microsaccade rates dropped, affirming the structure's role in producing these movements.

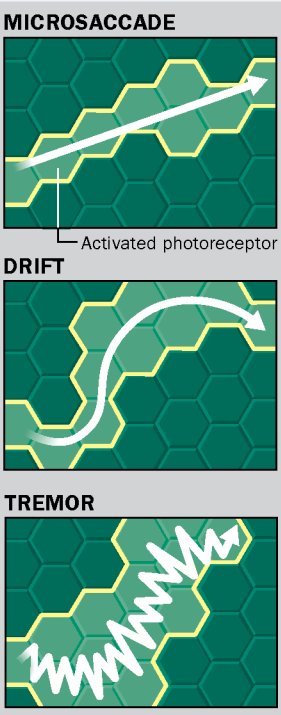
Together with earlier behavioral studies conducted by Rolf's team and ours, among others, these findings demonstrate that saccades and microsaccades are turned out in a similar manner. Understanding the structure in the brain that creates microsaccades may bring scientists one step closer to understanding the engine behind much of our ability to perceive objects and locate them in a busy visual scene. This knowledge also gives us a place in the brain to look if something goes wrong.

Errant Glances

To see normally, the superior colliculus, along with other parts of the nervous system, must calibrate how much your eyes move when they fixate. Too few of these

More Ways to Move

When your eyes are staring at something, they move nonetheless. Scientists have identified three types of fixational eye movements: microsaccades (straight lines), drifts (wavy lines) and tremor (zigzags overlaying drifts). Microsaccades are the largest of the fixational eye movements, carrying an image across as many as several hundred of the eye's photoreceptor (light-detecting) cells. Tremor is the smallest of the fixational eye movements, its motion no bigger than the size of one of these cells. Drifts are slow meanderings that occur between the fast, linear microsaccades. Investigators have not yet identified specific functions for each of these eye movements in vision, however.



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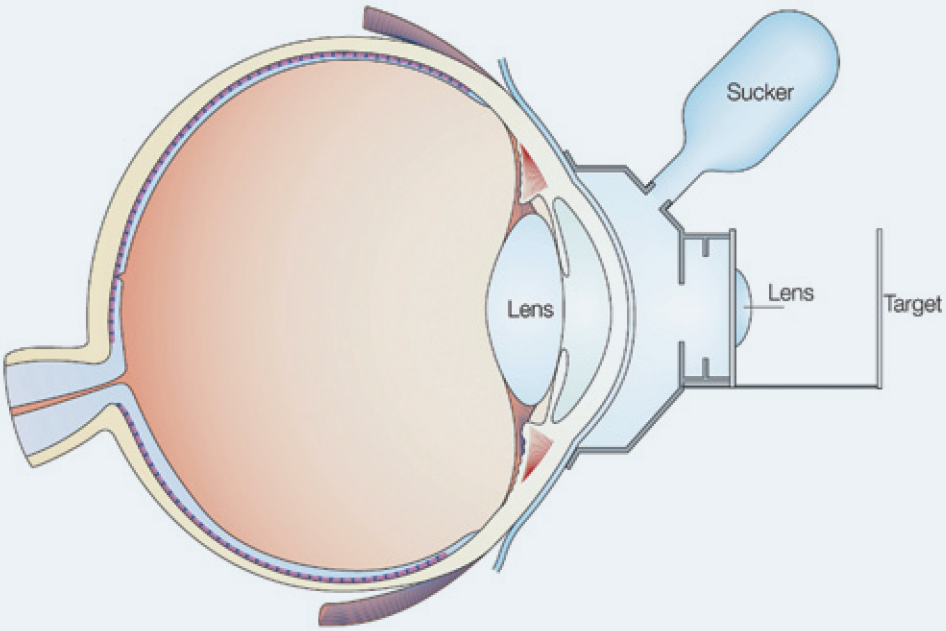

Stopping the Eyes

In the early 1950s some research teams succeeded in effectively freezing the visual scene 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. With the use of 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 the eye. They transmit the eye-position data to a projection system that moves the image with the eye.

FROM "THE ROLE OF FIXATIONAL EYE MOVEMENTS IN VISUAL PERCEPTION," BY SUSANA MARTINEZ-CONDE, STEPHEN L. MACKNIK AND DAVID H. HUBEL, IN *NATURE REVIEWS NEUROSCIENCE*, VOL. 5; MARCH 2004

tiny shifts, as we have seen, can cause stationary objects to fade away. But too much motion can create blurred and unstable vision. Understanding how the oculomotor system achieves such a balance might one day enable doctors to make adjustments if it gets out of whack, as it can when certain disorders of the nervous system strike.

For instance, abnormal fixational eye movements often accompany amblyopia, the most common form of blindness in young people. People with amblyopia may have trouble seeing details even if their eyes are physically normal because of abnormal development in the visual parts of the brain. In severe amblyopia, too few microsaccades, along with excessive drift of the eyes, can cause even large parts of the visual scene to fade away when a person is focusing on something. In one case reported in the literature, a patient with an amblyopic eye "made saccades to revive the faded or blanked-out portions" of an image. The observation that saccades counteract fading in people with amblyopia is likely related to our finding that microsaccades do the same in healthy observers. Understanding the role of saccades and microsaccades in this disorder might one day spawn new treatments that ameliorate vision loss because of it.

Recently our laboratories teamed up with Case Western Reserve University neurologists R. John Leigh and Alessandro Serra to study microsaccade abnormalities in people with progressive supranuclear palsy (PSP), a disease similar to Parkinson's. In PSP, patients first display parkinsonian symptoms: they become unstable and fall often; their movement slows; and their bodies stiffen. In addition, however, PSP patients have trouble shifting their gaze between distant and near objects. The symptoms that characterize these diseases arise from distinctive patterns of neuronal degeneration. In Parkinson's, the loss occurs primarily in the substantia nigra, which contributes to body control. Gaze difficulties in PSP result from more widespread neuronal degeneration affecting the brain stem, frontal lobes, basal ganglia and cerebellum.

In its initial stages, PSP is often misdiagnosed as Parkinson's, which can be problematic because the standard treat-

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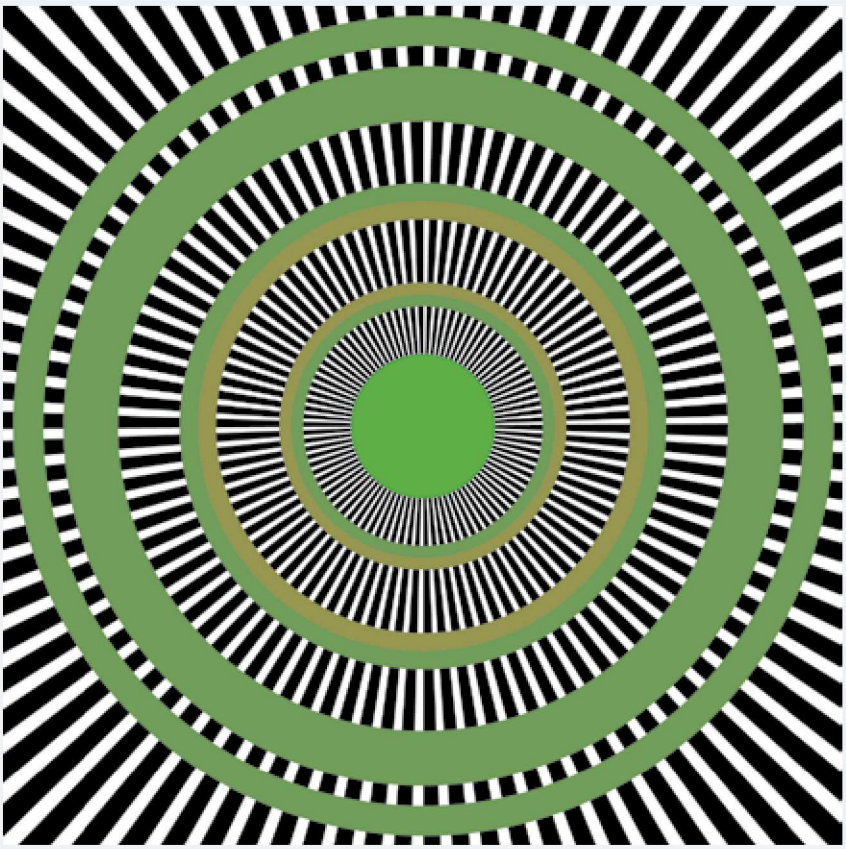
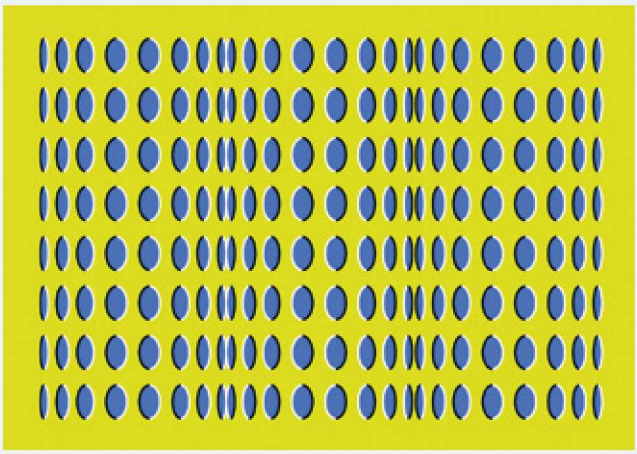
Mystery Solved

Look at the center of the image at the right and notice that the concentric green rings appear to fill with illusory motion, as if millions of tiny and barely visible cars were circling rapidly around a track. For almost 200 years artists, psychologists and neuroscientists have debated whether this type of striking illusory motion originates in the eye or in the brain, and for almost two decades the controversy has centered on the motion perceived in this painting, called *Enigma,* created by op-artist Isia Léviant. The evidence was conflicting until we found, in collaboration with our colleagues, neuroscientist Xoana G. Troncoso and graduate student Jorge Otero-Millan, both then at the Barrow Neurological Institute, that the perceived motion is driven by tiny shifts of the eyes called microsaccades.



***Enigma* illusion**

A few years ago one of us (Martinez-Conde) noticed that the speed of illusory motion in *Enigma* was not immutable across time but depended on how precisely a person fixed his or her gaze. If the individual held his or her eyes very still while staring carefully at the center of the image, the motion seemed to decrease and occasionally come to a full stop. Conversely, when he or she focused loosely, the movement seemed to speed up. Our previous research had shown that strict fixation suppresses the production of microsaccades, with dramatic effects on visibility. It followed that microsaccades may drive the perception of illusory motion under normal (loose) fixation conditions.



Roller illusion

To test this idea, we asked volunteers to stare steadily at a small spot at the center of an *Enigma*-like pattern while we measured their eye movements. Subjects had to press a button whenever the motion appeared to slow down or stop and release it whenever the motion sped up. As we predicted, microsaccades increased in frequency just before people saw faster motion and became sparser just prior to the slowing or halting of the motion. The results, published in 2008, proved for the first time that the illusory motion starts in the eye.

Microsaccades probably also underlie the illusory spinning in the picture at the left. If you let your eyes wander around the pattern, the three "rollers" will appear to spin. But hold your gaze steady on one of the blue spots, and the motion will slow or even pause. Because holding the eyes still stops the action, we speculate that microsaccades may be required to see it.

—S.M.-C. and S.L.M.

COURTESY OF JORGE OTERO-MILLAN *Barrow Neurological Institute (top);*
COURTESY OF AKIYOSHI KITAOKA *Ritsumeikan University (bottom)*

ment for Parkinson's, L-dopa, does not work in these patients. In research published earlier this year, we showed that the eye movements produced by PSP patients are different from those in healthy subjects and that normal microsaccades are very rare in PSP. We hope that our findings will ultimately help doctors diagnose accurately and early on who has this disorder. In addition, these results may assist researchers in evaluating the efficacy of drugs for PSP that are currently under development.

Private Eyes

Beyond their function in vision, microsaccades may reveal some of what we are thinking. Even when we are looking at one thing, our attention may be aimed at something else. Recent research suggests that microsaccades can reveal such objects of attraction because the direction of microsaccades, instead of being totally random, may point to them—even if your eyes are directed elsewhere. Hafed, then at McGill University, and his colleague vision scientist James J. Clark asked people to focus on a spot in the middle of a computer screen but to pay attention to another spot that appeared elsewhere. The peripheral spot changed color at the end of each trial, and every subject had to report the color change by pressing a button. Hafed and Clark found that the subjects' microsaccades were biased in the direction of their attention. Thus, your microsaccades may point toward that delicious doughnut you want to eat—or the attractive guy or gal standing across the room—even if you are averting your eyes from these temptations. These covert shifts of attention seem to control the direction of microsaccades.

Microsaccade frequency can also betray your attentional spotlight. Computational neuroscientist Ralf Engbert and cognitive psychologist Reinhold Kliegl of the University of Potsdam found that when something suddenly pops up in the periphery of your field of view, the microsaccade rate plummets briefly and then rapidly rebounds to a frequency faster than normal. The microsaccades also shift in the direction of the object. So both their direction and rate can signal sudden changes in your surroundings that attract your notice even if you look the other way.

You cannot read another person's mind by scrutinizing his or her microsaccades just yet. Only scientists working in a laboratory can detect and measure these minuscule eye movements. That fact may be welcome, assuming you do not want your co-worker—or spouse—decoding your thoughts. M

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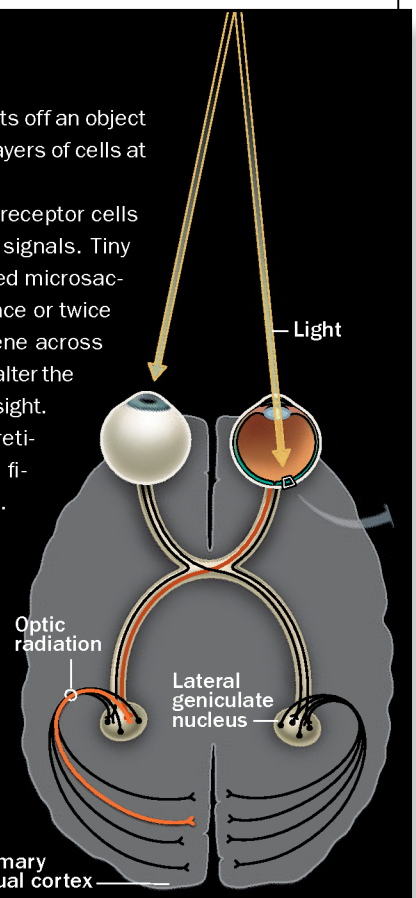
Moving Pictures

Vision begins when light reflects off an object and hits the retina, several layers of cells at the back of both eyes.

To the rear of the retina, photoreceptor cells transform light energy into neural signals. Tiny subconscious eye movements called microsaccades refresh the neural activity once or twice a second by shifting the visual scene across the retina. Microsaccades similarly alter the responses of other cells involved in sight.

The neural impulses from the retina zip along a cable of a million fibers—the optic nerve—to the brain. In the brain, visual signals stop first at the lateral geniculate nucleus in the thalamus. Then nerves called the optic radiations carry those signals to the primary visual cortex at the back of the brain, where neurons start to assemble and make sense of the information.



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- Martinez-Conde Laboratory: **http://smc.neuralcorrelate.com**