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NEUROSCIENCE

# THE LANGUAGE OF THE BRAIN

*The brain makes sense of our experiences by focusing closely on the timing of the impulses that flow through billions of nerve cells*

*By Terry Sejnowski and Tobi Delbruck*

## OUR BRAINS ARE BETTER THAN GOOGLE OR THE BEST ROBOT FROM iROBOT.

We can instantly search through a vast wealth of experiences and emotions. We can immediately recognize the face of a parent, spouse, friend or pet, whether in daylight, darkness, from above or sideways—a task that the computer vision system built into the most sophisticated robots can accomplish only haltingly. We can also multitask effortlessly when we extract a handkerchief from a pocket and mop our brow while striking up a conversation with an acquaintance. Yet designing an electronic brain that would allow a robot to perform this simple combination of behaviors remains a distant prospect.



*Illustration by Kenn Brown, Mondolithic Studios*

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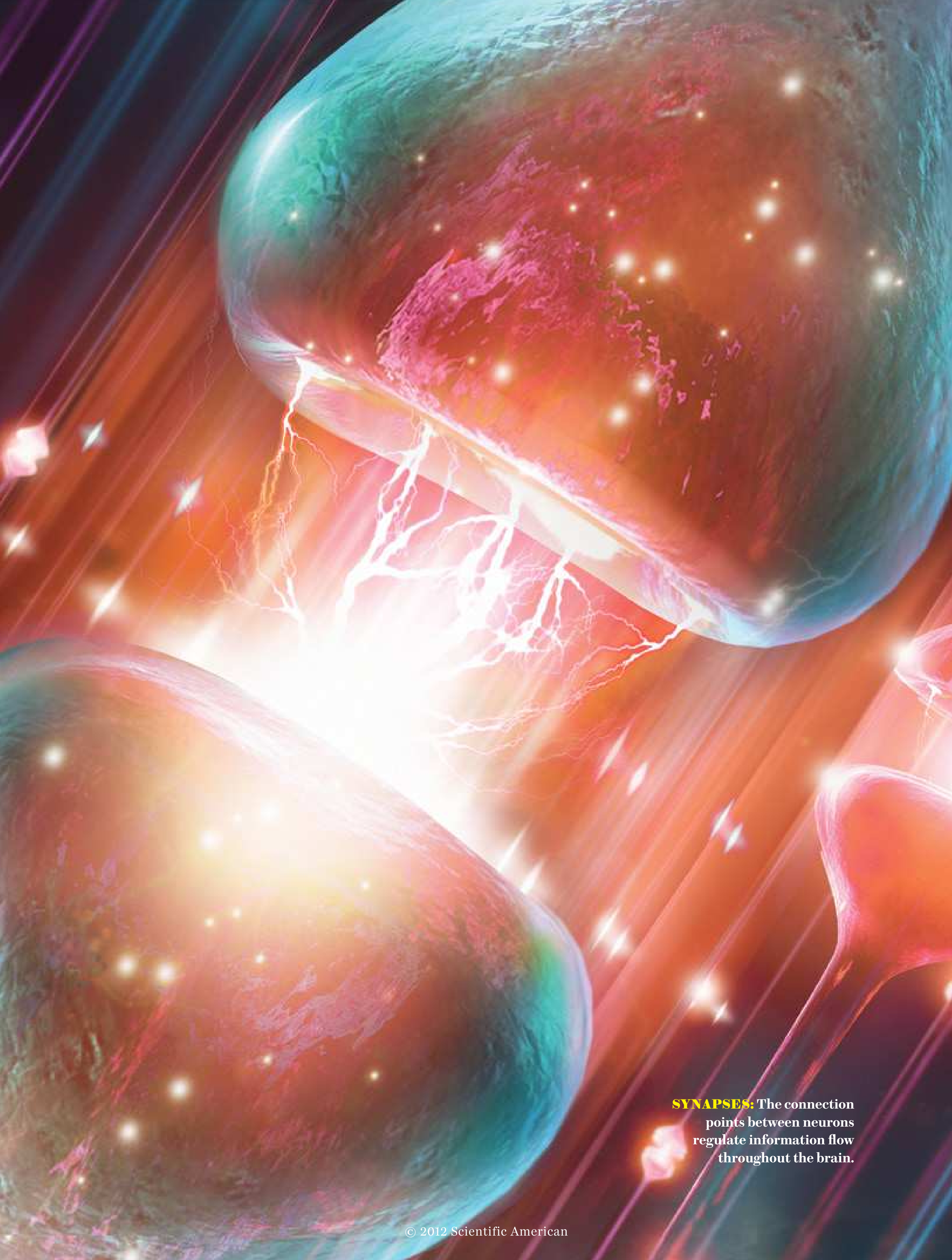

**SYNAPSES:** The connection points between neurons regulate information flow throughout the brain.

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How does the brain pull all this off, given that the complexity of the networks inside our skull—trillions of connections among billions of brain cells—rivals that of the Internet? One answer is energy efficiency: when a nerve cell communicates with another, the brain uses just a millionth of the energy that a digital computer expends to perform the equivalent operation. Evolution, in fact, may have played an important role in pushing the three-pound organ toward ever greater energy efficiencies.

Parsimonious energy consumption cannot be the full explanation, though, given that the brain also comes with many built-in limitations. One neuron in the cerebral cortex, for instance, can respond to an input from another neuron by firing an impulse, or a "spike," in thousandths of a second—a snail's pace compared with the transistors that serve as switches in computers, which take billionths of a second to switch on. The reliability of the neuronal network is also low: a signal traveling from one cortical cell to another typically has only a 20 percent possibility of arriving at its ultimate destination and much less of a chance of reaching a distant neuron to which it is not directly connected.

Neuroscientists do not fully understand how the brain manages to extract meaningful information from all the signaling that goes on within it. The two of us and others, however, have recently made exciting progress by focusing new attention on how the brain can efficiently use the timing of spikes to encode information and rapidly solve difficult computational problems. This is because a group of spikes that fire almost at the same moment can carry much more information than can a comparably sized group that activates in an unsynchronized fashion.

Beyond offering insight into the most complex known machine in the universe, further advances in this research could lead to entirely new kinds of computers. Already scientists have built "neuromorphic" electronic circuits that mimic aspects of the brain's signaling network. We can build devices today with a million electronic neurons, and much larger systems are planned. Ultimately investigators should be able to build neuromorphic computers that function much faster than modern computers but require just a fraction of the power [see "Neuromorphic Microchips," by Kwabena Boahen; Scientific American, May 2005].

## CELL CHATTER

LIKE MANY OTHER NEUROSCIENTISTS, we often use the visual system as our test bed, in part because its basic wiring diagram is well understood. Timing of signals there and elsewhere in the brain has long been suspected of being a key part of the code that the brain uses to decide whether information passing through the network is meaningful. Yet for many decades these ideas were neglected because timing is only important when compared between different parts of the brain, and it was hard to measure activity of more than one neuron at a time. Recently, however, the practical development of computer models of the nervous system and new results from experimental and theoretical neuroscience have spurred interest in timing as a way to better understand how neurons talk to one another.

Brain cells receive all kinds of inputs on different timescales. The microsecond-quick signal from the right ear must be reconciled with the slightly out-of-sync input from the left. These rapid responses contrast with the sluggish stream of hormones coursing through the bloodstream. The signals most important for this discussion, though, are the spikes, which are sharp rises in voltage that course through and between neurons. For cell-to-cell communication, spikes lasting a few milliseconds handle immediate needs. A neuron fires a spike after deciding that the number of inputs urging it to switch on outweigh the number telling it to turn off. When the decision is made, a spike travels down the cell's axon (somewhat akin to a branched electrical wire) to its tips. Then the signal is relayed chemically through junctions, called synapses, that link the axon with recipient neurons.

In each eye, 100 million photoreceptors in the retina respond to changing patterns of light. After the incoming light is processed by several layers of neurons, a million ganglion cells at the back of the retina convert these signals into a sequence of spikes that are relayed by axons to other parts of the brain, which in turn send spikes to still other regions that ultimately give rise to a conscious perception. Each axon can carry up to several hundred spikes each second, though more often just a few spikes course along the neural wiring. All that you perceive of the visual world—the shapes, colors and movements of everything around you—is coded into these rivers of spikes with varying time intervals separating them.

Monitoring the activity of many individual neurons at once is critical for making sense of what goes on in the brain but has long been extremely challenging. In 2010, though, E. J. Chichilnisky of the Salk Institute for Biological Studies in La Jolla, Calif., and his colleagues reported in *Nature* that they had achieved the monumental task of simultaneously recording all the spikes from hundreds of neighboring ganglion cells in monkey retinas. (*Scientific American* is part of Nature Publishing Group.) This achievement made it possible to trace the specific photoreceptors that fed into each ganglion cell. The growing ability to record spikes from many neurons simultaneously will assist in deciphering meaning from these codelike brain signals.

For years investigators have used several methods to interpret, or decode, the meaning in the stream of spikes coming from the retina. One method counts spikes from each axon separately over some period: the higher the firing rate, the stronger the signal. The information conveyed by a variable firing rate, a rate code, relays features of visual images, such as location in space, regions of differing light contrast, and where motion occurs, with each of these features represented by a given group of neurons.

### IN BRIEF

**Three pounds of nerve tissue** underneath the skull are capable of perceiving, thinking and acting with a finesse that cannot be matched by any computer.

**The brain achieves** this feat of cognition, in part, by carefully timing the signals that flash across the trillions of connections that link billions of brain cells.

**Seeing a flower pot** causes groups of neurons to fire in a brief time interval to activate a part of the brain that registers that particular object at just that one moment.

**Understanding how** this timing system works will both lead to better understanding of our behavior and enable the building of new computing and electronic equipment that, like the brain, functions more efficiently than conventional digital machines.



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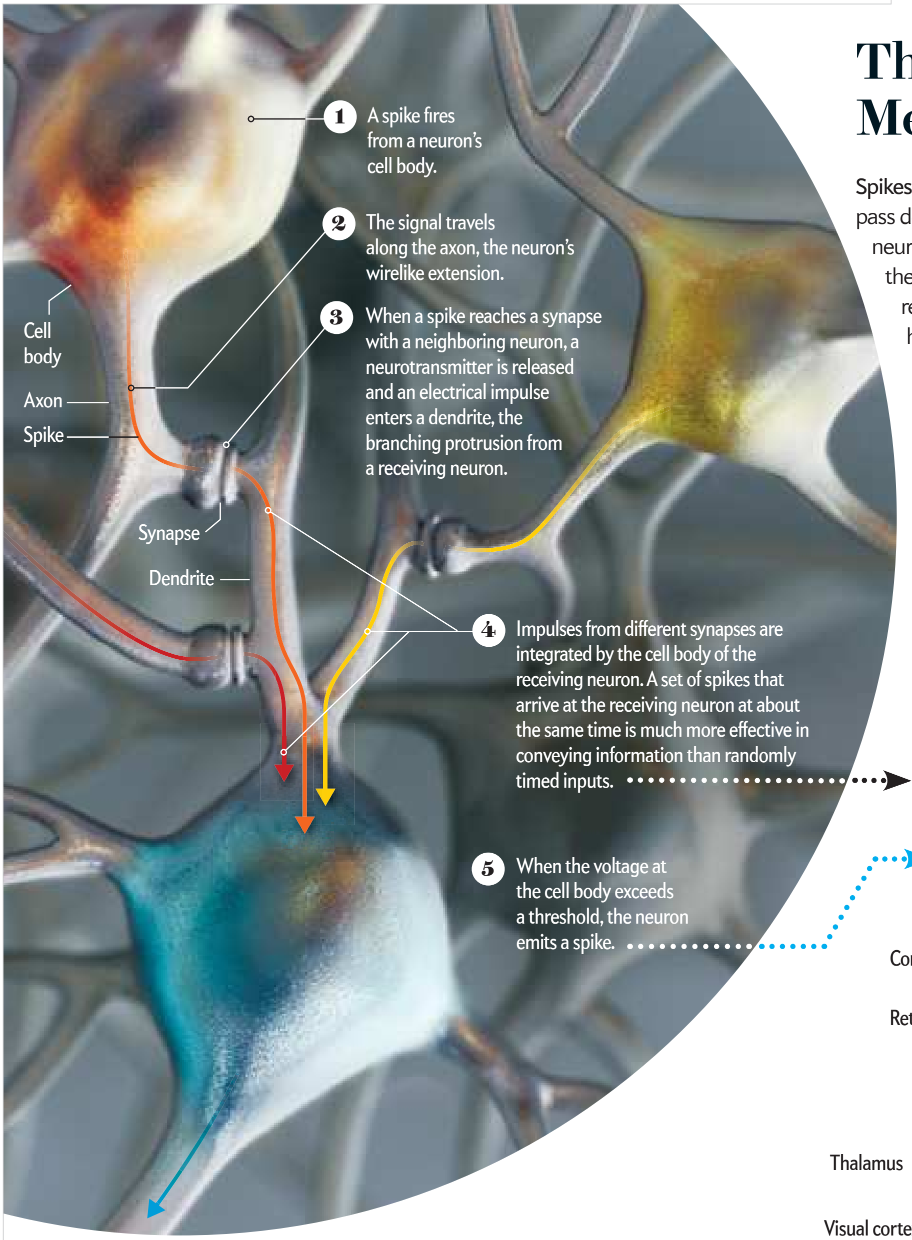
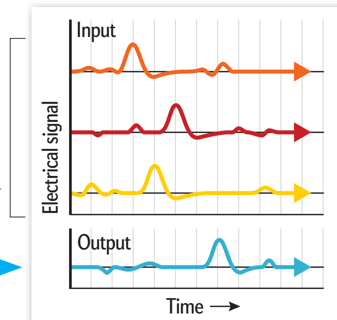
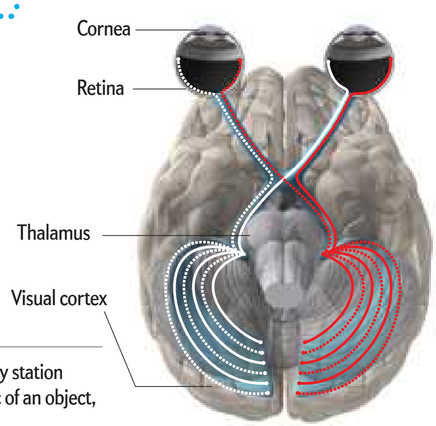
# The Brain's Fast Messaging Link

Spikes—millisecond rises in voltage that pass down axons from cell bodies to other neurons—are the communication signals the brain uses to provide an immediate response to an event. New research has shown that coordinated timing of spikes lends efficiency to a network of brain cells that encompasses trillions of connections among neurons.




Spikes that arrive at a neuron within a narrow time window of a few milliseconds—shown below as colored blips—can trigger the firing of that neuron.




**What the Eyes Tell the Brain**
"Seeing" occurs when spikes generated by cells within the eye in response to an object move on to the relay station of the thalamus and then to the visual cortex. Properly timed spikes, each representing some characteristic of an object, such as color or spatial orientation, are integrated in the cortex to form a perception of the whole object.

Information is also transmitted by relative timing—when one neuron fires in close relation to when another cell spikes. Ganglion cells in the retina, for instance, are exquisitely sensitive to light intensity and can respond to a changing visual scene by transmitting spikes to other parts of the brain. When multiple ganglion cells fire at almost the same instant, the brain suspects that they are responding to an aspect of the same physical object. Horace Barlow, a leading neuroscientist at the University of Cambridge, characterized this phenomenon as a set of "suspicious coincidences." Barlow referred to the observation that each cell in the visual cortex may be activated by a specific physical feature of an object (say, its color or its orientation within a scene). When several of these cells switch on at the same time, their combined activation constitutes a suspicious coincidence because it may only occur at a specific time for a unique object. Apparently the brain takes such synchrony to mean that the signals are worth noting because the odds of such coordination occurring by chance are slim.

Electrical engineers are trying to build on this knowledge to create more efficient hardware that incorporates the principles

*Illustration by Emily Cooper*



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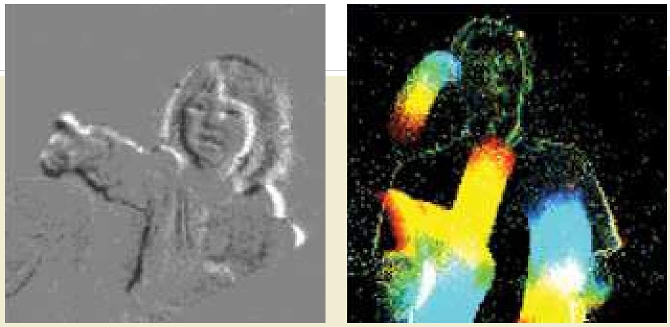
## The Retina Inspires a New Kind of Camera

### Technology emerges from studying the speed and efficiency of the brain's visual processing



**IF IT MOVES, SHOOT IT:** The DVS captures only parts of the scene in which pixels change in brightness from one moment to the next. As contrast changes in the image of a child (*left*), pixels become brighter or darker. For the juggler (*right*), recent ball movements glow red and the oldest ones flash blue.

**Traditional digital video cameras** are surprisingly inefficient. They snap 24 frames a second to capture the varying intensities of light that make up the different parts of a visual scene. Each pixel, or discrete picture element in an image, records the average intensity over the past 40 milliseconds, the time it takes a fast-hit tennis ball to move about 1.5 meters. As a result, the cameras produce an enormous flood of data that consumes a lot of processing time.

Aiming for more efficiency, one of us (Delbruck) and his colleagues at the Institute of Neuroinformatics at the University of Zurich have developed a new type of camera that mimics the way parts of the retina encode images for our brain. Like the retina, the camera—called the Dynamic Vision Sensor, or DVS—senses only the parts of a scene that change when any pixel detects a change in brightness from the existing recorded value. The camera can thus capture even fast-moving objects using just a trickle of data.

The pixels in the DVS behave something like certain retinal ganglion cells in that they also emit an electrical spike when brightness changes. The camera can record a shift of light intensity in the blink of a microsecond, so the DVS can track high-speed motion better than the millisecond speeds of ordinary cameras that capture a scene frame by frame.

Because of the sparse yet information-packed output of the DVS, the camera is ideal as a sentinel, a detector of anything that moves, whether a car, pedestrian traffic, or an elderly person who slips and falls. As a result of the camera's speed, the DVS has been incorporated into a robot that blocks balls shot at a goal, as well as a pencil-balancing robot, a car that follows a line drawn in chalk, and sensors that track particles in moving fluids or that interpret human gestures. The shoot-what-changes approach to processing visual information has started to attract broader interest among technology designers. A group at Weill Cornell Medical College and their collaborators recently reported on an artificial retina prosthesis that processes light using this method, a nod to the sparse elegance with which biology sometimes functions. *—T.S. and T.D.*

of spike timing when recording visual scenes. One of us (Delbruck) has built a camera that emits spikes in response to changes in a scene's brightness, which enables the tracking of very fast moving objects with minimal processing by the hardware to capture images [*see box above*].

#### INTO THE CORTEX

NEW EVIDENCE ADDS PROOF that the visual cortex attends to temporal clues to make sense of what the eye sees. The ganglion cells in the retina do not project directly to the cortex but relay signals through neurons in the thalamus, deep within the brain's midsection. This region in turn must activate 100 million cells in the visual cortex in each hemisphere at the back of the brain before the messages are sent to higher brain areas for conscious interpretation.

We can learn something about which spike patterns are most effective in turning on cells in the visual cortex by examining the connections from relay neurons in the thalamus to cells known as spiny stellate neurons in a middle layer of the visual cortex. In 1994 Kevan Martin, now at the Institute of Neuroinformatics at the University of Zurich, and his colleagues reconstructed the thalamic inputs to the cortex and found that they account for only 6 percent of all the synapses on each spiny stellate cell. How, then, everyone wondered, does this relatively weak visual input, a mere trickle, manage to reliably communicate with neurons in all layers of the cortex?

Cortical neurons are exquisitely sensitive to fluctuating inputs and can respond to them by emitting a spike in a matter of a few milliseconds. In 2010 one of us (Sejnowski), along with Hsi-Ping Wang and Donald Spencer of the Salk Institute and Jean-Marc Fellous of the University of Arizona, developed a detailed computer model of a spiny stellate cell and showed that even though a single spike from only one axon cannot cause one of these cells to fire, the same neuron will respond reliably to inputs from as few as four axons projecting from the thalamus if the spikes from all four arrive within a few milliseconds of one another. Once inputs arrive from the thalamus, only a sparse subset of the neurons in the visual cortex needs to fire to represent the outline and texture of an object. Each spiny stellate neuron has a preferred visual stimulus from the eye that produces a high firing rate, such as the edge of an object with a particular angle of orientation.

In the 1960s David Hubel of Harvard Medical School and Torsten Wiesel, now at the Rockefeller University, discovered that each neuron in the relevant section of the cortex responds strongly to its preferred stimulus only if activation comes from a specific part of the visual field called the neuron's receptive field. Neurons responding to stimulation in the fovea, the central region of the retina, have the smallest receptive fields—about the size of the letter e on this page. Think of them as looking at the world through soda straws. In the 1980s John Allman of the Cal-

COURTESY OF TOBI DELBRUCK (*left*); COURTESY OF PATRICK LICHTSTEINER AND TOBI DELBRUCK (*right*)



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ifornia Institute of Technology showed that visual stimulation from outside the receptive field of a neuron can alter its firing rate in reaction to inputs from within its receptive field. This "surround" input puts the feature that a neuron responds to into the context of the broader visual environment.

Stimulating the region surrounding a neuron's receptive field also has a dramatic effect on the precision of spike timing. David McCormick, James Mazer and their colleagues at Yale University recently recorded the responses of single neurons in the cat visual cortex to a movie that was replayed many times. When they narrowed the movie image so that neurons triggered by inputs from the receptive field fired (no input came from the surrounding area), the timing of the signals from these neurons had a randomly varying and imprecise pattern. When they expanded the movie to cover the surrounding area outside the receptive field, the firing rate of each neuron decreased, but the spikes were precisely timed.

The timing of spikes also matters for other neural processes. Some evidence suggests that synchronized timing—with each spike representing one aspect of an object (color or orientation)—functions as a means of assembling an image from component parts. A spike for "pinkish red" fires in synchrony with one for "round contour," enabling the visual cortex to merge these signals into the recognizable image of a flower pot.

## ATTENTION AND MEMORY

OUR STORY SO FAR has tracked visual processing from the photoreceptors to the cortex. But still more goes into forming a perception of a scene. The activity of cortical neurons that receive visual input is influenced not only by those inputs but also by excitatory and inhibitory interactions between cortical neurons. Of particular importance for coordinating the many neurons responsible for forming a visual perception is the spontaneous, rhythmic firing of a large number of widely separated cortical neurons at frequencies below 100 hertz.

Attention—a central facet of cognition—may also have its physical underpinnings in sequences of synchronized spikes. It appears that such synchrony acts to emphasize the importance of a particular perception or memory passing through conscious awareness. Robert Desimone, now at the Massachusetts Institute of Technology, and his colleagues have shown that when monkeys pay attention to a given stimulus, the number of cortical neurons that fire synchronized spikes in the gamma band of frequencies (30 to 80 hertz) increases, and the rate at which they fire rises as well. Pascal Fries of the Ernst Strüngmann Institute for Neuroscience in cooperation with the Max Planck Society in Frankfurt found evidence for gamma-band signaling between distant cortical areas.

Neural activation of the gamma-frequency band has also attracted the attention of researchers who have found that patients with schizophrenia and autism show decreased levels of this type of signaling on electroencephalographic recordings. David Lewis of the University of Pittsburgh, Margarita Behrens of the Salk Institute and others have traced this deficit to a type of cortical neuron called a basket cell, which is involved in synchronizing spikes in nearby circuits. An imbalance of either inhibition or excitation of the basket cells seems to reduce synchronized activity in the gamma band and may thus explain some of the physiological underpinnings of these neurological disorders. Interestingly, patients with schizophrenia do not perceive some visual illusions, such as the tilt illusion, in which a person typically misjudges the tilt of a line because of the tilt of nearby lines. Similar circuit abnormalities in the prefrontal cortex may be responsible for the thought disorders that accompany schizophrenia.

When it comes to laying down memories, the relative timing of spikes seems to be as important as the rate of firing. In particular, the synchronized firing of spikes in the cortex is important for increasing the strengths of synapses—an important process in forming long-term memories. A synapse is said to be strengthened when the firing of a neuron on one side of a synapse leads the neuron on the other side of the synapse to register a stronger response. In 1997 Henry Markram and Bert Sakmann, then at the Max Plank Institute for Medical Research in Heidelberg, discovered a strengthening process known as spike-timing-dependent plasticity, in which an input at a synapse is delivered at a frequency in the gamma range and is consistently followed within 10 milliseconds by a spike from the neuron on the other side of the synapse, a pattern that leads to enhanced firing by the neuron receiving the stimulation. Conversely, if the neuron on the other side fires within 10 milliseconds before the first one, the strength of the synapse between the cells decreases.

Some of the strongest evidence that synchronous spikes may be important for memory comes from research by György Buzsáki of New York University and others on the hippocampus, a brain area that is important for remembering objects and events. The spiking of neurons in the hippocampus and the cortical areas that it interacts with is strongly influenced by synchronous oscillations of brain waves in a range of frequencies from four to eight hertz (the theta band), the type of neural activity encountered, for instance, when a rat is exploring its cage in a laboratory experiment. These theta-band oscillations can coordinate the timing of spikes and also have a more permanent effect in the synapses, which results in long-term changes in the firing of neurons.

## A GRAND CHALLENGE AHEAD

NEUROSCIENCE IS AT A TURNING POINT as new methods for simultaneously recording spikes in thousands of neurons help to reveal key patterns in spike timing and produce massive databases for researchers. Also, optogenetics—a technique for turning on genetically engineered neurons using light—can selectively activate or silence neurons in the cortex, an essential step in establishing how neural signals control behavior. Together, these and other techniques will help us eavesdrop on neurons in the brain and learn more and more about the secret code that the brain uses to talk to itself. When we decipher the code, we will not only achieve an understanding of the brain's communication system, we will also start building machines that emulate the efficiency of this remarkable organ. SA


MORE TO EXPLORE

Terry Sejnowski's 2008 Wolfgang Pauli Lectures on how neurons compute and communicate: www.podcast.ethz.ch/podcast/episodes/?id=607

**Neuromorphic Sensory Systems.** Shih-Chii Liu and Tobi Delbruck in *Current Opinion in Neurobiology,* Vol. 20, No. 3, pages 288–295; June 2010. http://tinyurl.com/bot7ag8


**SCIENTIFIC AMERICAN ONLINE**
Watch a video about a motion-sensing video camera that uses spikes for imaging at ScientificAmerican.com/oct2012/dvs



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