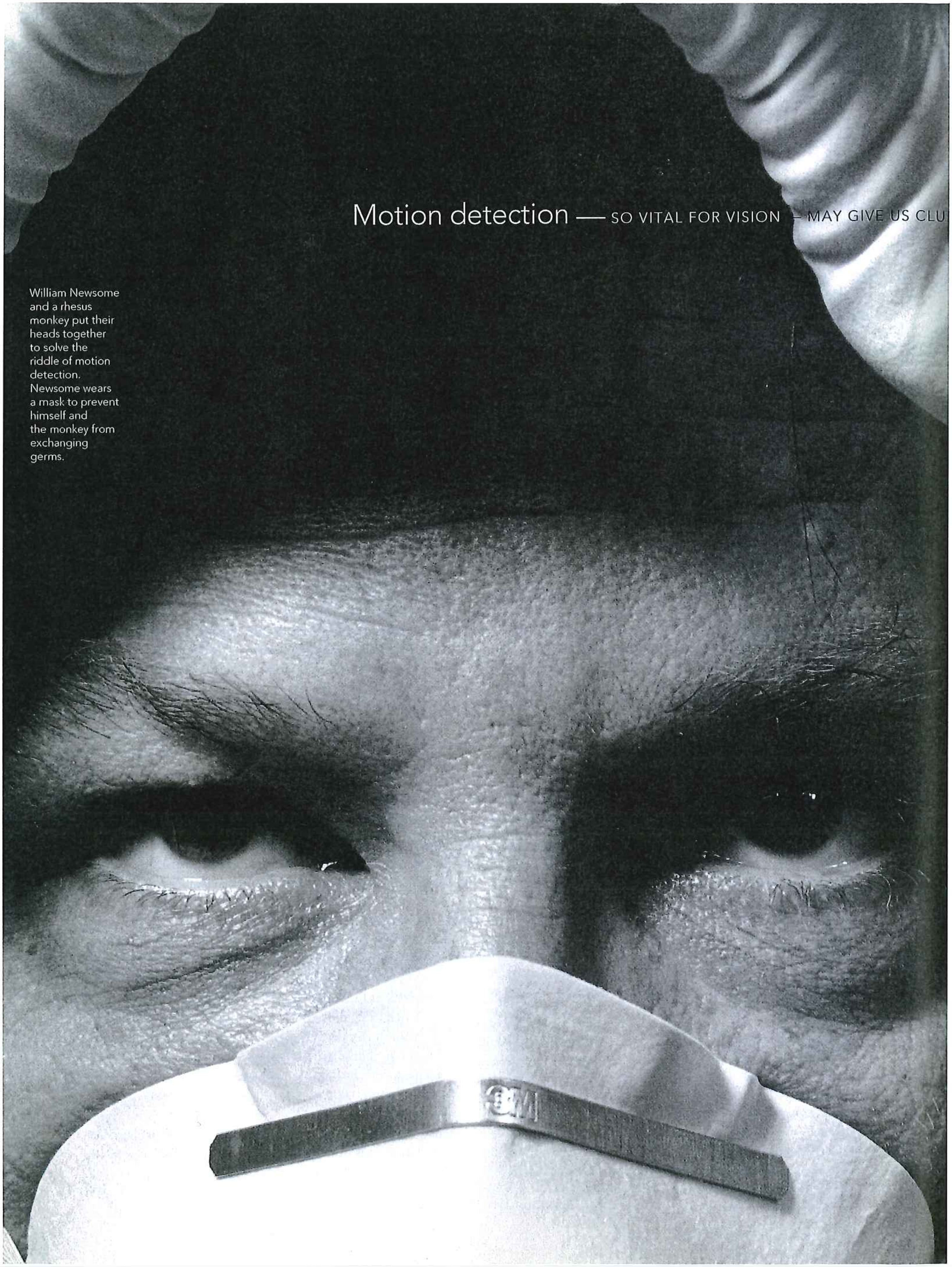
Motion detection — SO VITAL FOR VISION — MAY GIVE US CLU

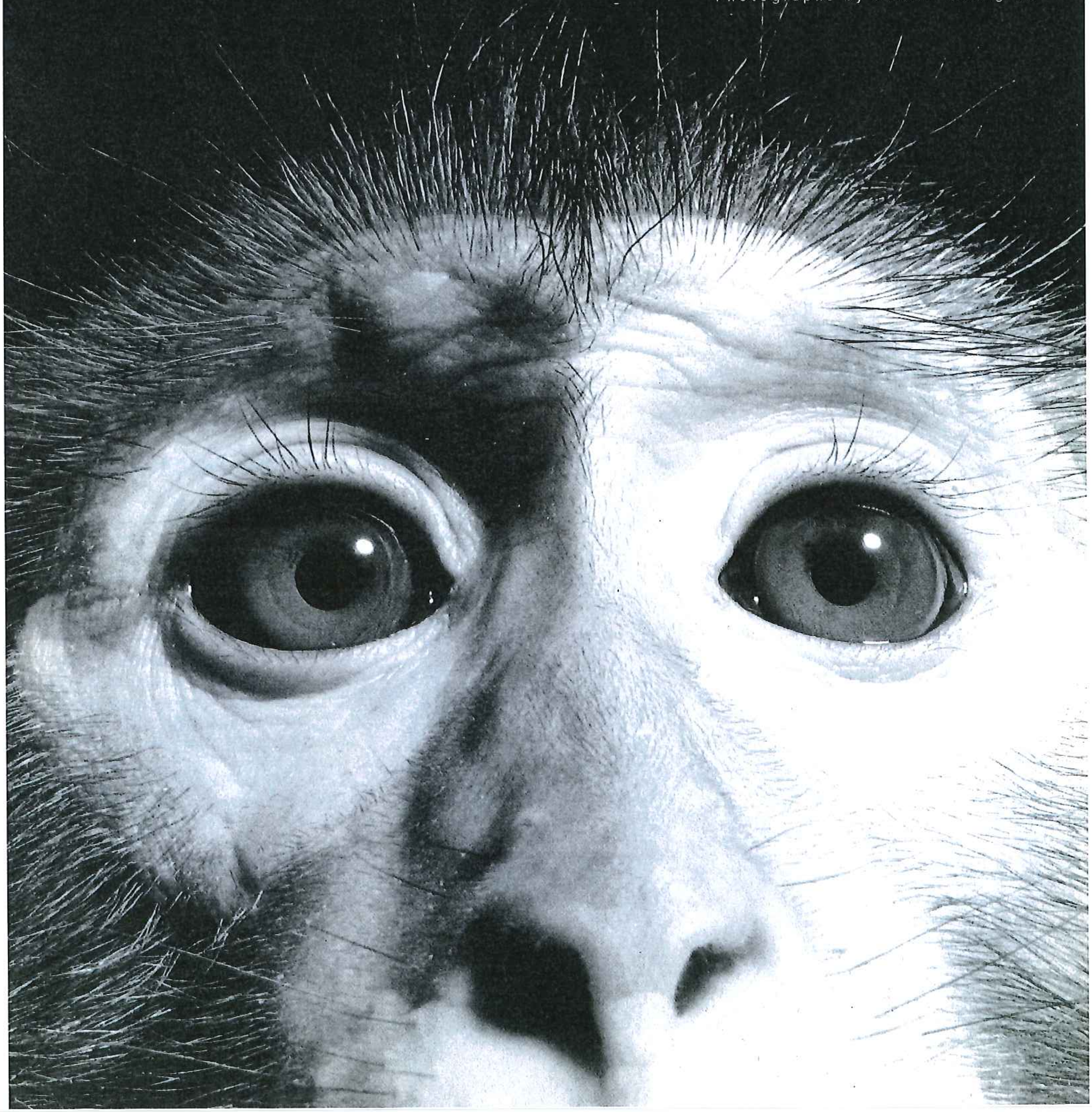


William Newsome and a rhesus monkey put their heads together to solve the riddle of motion detection. Newsome wears a mask to prevent himself and the monkey from exchanging germs.

the eye-brain connection

ABOUT THE BASIS OF CONSCIOUSNESS.

by William A. Wells
Photographs by Robert Holmgren



FALLING WATER MOVES, AND CLIFF FACES DO NOT. Or so it appears at first. But stare long enough at the water tumbling over a waterfall, then transfer your attention to the nearby cliff face, and the cliff face also appears to be moving, slowly and upwards.

Our minds play tricks on us, but most of the time our motion detectors behave and serve as an essential tool for survival. Without the ability to detect motion — a situation faced by some humans with specific tumor- or stroke-induced brain damage — life becomes complicated, indeed. They see the world as a series of stills. Cars do not move but unexpectedly show up in new locations, and waterfalls appear to be frozen all year round.

For many predators, motion detection *is* vision — if a meal is not moving, it is not seen — and even humans have difficulty detecting objects in their peripheral vision unless the objects are moving.

But motion detection is no simple task. The waterfall illusion reminds us that although the eye acts somewhat like a camera, the brain must convert the two-dimensional image on the back of the eye to a three-dimensional representation. Vision, and motion in particular, must be computed.

"What your visual system 'sees' is not necessarily reality, but an inference from reality," explains William Newsome, PhD, professor of neurobiology at Stanford. Newsome's task is to decipher just how the brain makes those inferences in detecting motion. That research has now put him in a unique position, one from which he can begin to ask questions about consciousness that have plagued philosophers for centuries. How, for example, do we create the internal image that constitutes our perception of the world around us? This is an easy question to ask, but the starting point for answering it is extraordinarily difficult to determine.

"We have a rich internal life — we have perception — and then, on the other hand, we have billions of neurons talking to each other," says Newsome. "Certainly, those two are related, but how? Bridging the gap is a huge task. How do we link the brain to the mind?"

One approach selects an accessible system, such as vision, and asks what happens in the two observable parts — the eyes and the muscles. The vision pathway begins when light rays fall on the eye and spark neurons into action, after which something mysterious happens, and finally other active neurons instruct muscles to move the eyes or the arms or the legs in response to the light. While other researchers have approached the brain from the side of the muscles, Newsome has come in from the eyes.

"Anything past the inside surface of the eye was a huge black box, even for some time after World War II," he says. But in 1959, David Hubel, MD, and Torsten Wiesel, MD, of Harvard Medical School found the first signs of the brain's image-processing ability. They defined V1, an area of the cortex at the back of the brain in which nerve cells are grouped in microscopic "columns." The cells in each column respond best to visual signals of a particular orientation. Thus, when a monkey is shown a diagonal bar, the few thousand cells in one column spring into action, while the cells in another respond only to a vertical bar. When presented with their preferred stimulus, the cells fire off repeated electrical signals but remain silent in response to other displays. "This," says Newsome, "is real analysis; this is real computing." That computing power is probably used to encode the shapes of objects.

Neurologically, it is a long way from the eyes to V1, but the neurons that carry the visual messages to V1 maintain a geographic map of the world. Columns at one extreme of V1 keep track of objects at the top of one's visual field — for instance, the sky — while columns at the other extreme track objects at the bottom.

This geographic map is also maintained in motion's equivalent of V1, an area called MT. Semir Zeki, PhD, at University College, London, found in 1971 that columns in the monkey's MT region responded selectively to bars of light moving in a particular direction. These columns and the V1 columns are "probably the fundamental building blocks of perception," Newsome says.

But in the early 1980s, when Newsome entered the field, this theory was far from proven. Just because MT responds to motion does not mean an animal needs it to detect motion. To show that the brain uses MT to detect motion, Newsome inactivated rhesus monkeys' MT regions with drugs. As expected, the treated monkeys performed poorly in motion-detection tasks. Perhaps they, like the brain-damaged patients, see the world as a series of stills.

The next step was to determine whether MT alone could account for the exquisite sensitivity of the motion-detection system. If MT is the major center of motion detection, it should be as sensitive as the whole animal.

To compare MT activity and animal performance directly, Newsome needed awake monkeys, able to report what they see. When Zeki looked for the motion-sensitive cells in MT, he could use anesthetized monkeys, since their brains remain activated by light.

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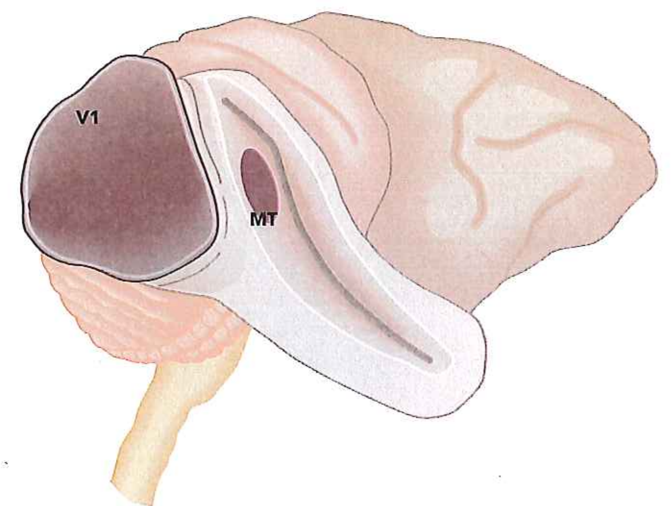


A monkey's brain
The V1 area serves as an image-processing center. Newsome believes the MT area probably serves to detect motion.

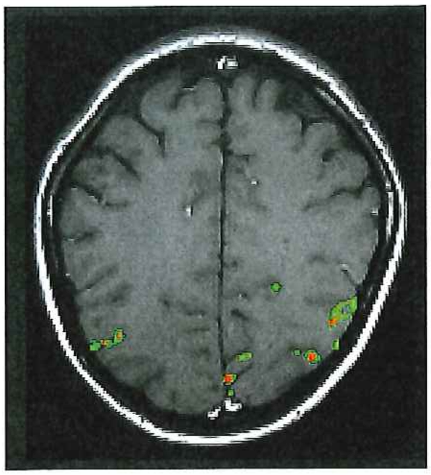
Newsome uses an electrode inserted into the monkey's brain to detect the blips of electricity produced by active neurons. The insult to the animal is minimal. The necessarily tiny electrode must be capable of picking up the signal from a single neuron with a diameter of about one-hundredth of a millimeter. And as the brain lacks pain receptors, only the skull needs to be anesthetized.

The first problem is to find the right part of the brain. Fortunately, the brain is laid out in a very predictable way, and Newsome knows exactly where to insert the electrode. When the electrode picks up the activity of neurons signaling in response to a moving-dot pattern viewed by the monkey, Newsome knows he has found the right place.

The dot pattern Newsome uses is reminiscent of a snowstorm with a variable wind setting. In the simplest case (with no wind), all the dots move in one direction. Newsome makes the display more ambiguous by increasing the number of dots moving in random directions. The pattern of motion becomes less and less obvious. When less than 6 percent of the dots are moving in the same direction, most humans (and monkeys) cannot discern any coherent motion. The dots become a blizzard, and we can't tell which way is up.

Once the electrode and the dot pattern are perfected, the long training period can begin. Over six months, the researchers use fruit juice rewards to coax the monkeys into following instructions. First the monkeys are trained to concentrate on a single bright spot on the screen, even while a moving-dot pattern appears elsewhere on the screen. Then, they are taught to move their eyes to indicate the direction of motion of the dot pattern. Of this strange collaboration, Newsome says, "If the monkey doesn't want to work, there is nothing I can do to make him do it." It also raises the question of who is training whom, he says. One monkey convinced Newsome to feed it special monkey biscuits every hour, as a means of extracting the monkey's continued cooperation.

A human's brain, seen as a magnetic-resonance image. The colored patches indicate increased neural activity in the MT area — a result of watching a moving-dot pattern.



When the time for experiments finally comes around, the experiments and reward strategies need to be carefully designed. "The monkey is not interested in telling the truth," explains Newsome, "but in getting the reward. He's going to report whatever you train him to report,"

In the first set of experiments, Newsome and graduate students compared the performance of the neurons in MT with the performance of the whole animal. One of the researchers inserted the electrode in MT and worked out the dot motion to best stimulate the "neuron of the day." Only when the dot pattern was in a particular part of space and when the dots were moving in a particular direction, did the neuron jump to life. The occasional click of electricity became a roar of current flowing through the neuron.

When Newsome turned up the wind factor and made the dot pattern ambiguous, the neurons gradually quit responding to their preferred stimulus, and the monkey made more and more mistakes. Amazingly, the neurons and the whole animal failed at the same level of ambiguity. "It was a one-to-one match — really beautiful," says Newsome.

Thus, individual MT neurons are sufficient to account for the performance of the whole animal — enough information exists in the MT region alone. This finding contrasts with the prevailing theories, which held that visual information is processed by networks of millions of neurons and that only the combination of all these neurons would give a response as sensitive as that of the whole animal.

This all sounds like conclusive proof of MT's importance, but to a scientist one burning question remains: Is the activity in MT actually used by the animal — is it hooked up to anything? If only Newsome could insert an artificial signal (by stimulating with the inserted electrode) and see a predicted behavior emerge. This was a long shot and, says Newsome, "I would never have trained the monkeys for six months to do this." But the monkeys had already been trained for the sensitivity tests, and all Newsome had to do was to add electricity rather than record it. After two of his postdoctoral fellows turned down the experiment, medical student Daniel Salzman took up the challenge. "We had to try it," says Newsome, "because if it worked, it would be spectacular."

Salzman used a tiny amount of electricity so that only one column of MT came alive. In the first test case, he stimulated a column that normally responded to upwards motion, while showing the monkey downward-moving dots. "Amazingly, the very first experiment worked," says Newsome. The monkey would normally signal the downwards motion correctly, but with the jolt of electricity in the "up" column, it more often signaled that the dots were moving up. Newsome was "incredibly suspicious," and immediately turned off the electrode. As predicted, the upwards bias went away.

Placing the electrode correctly was a tricky proposition, and not all experiments were affected by the electrode. But in the 60 percent that were affected, the monkey was biased toward the direction preferred by the electrode's column 97 percent of the time. Some of the results were spectacular. "The tenth experiment, we got our first whopper," says Newsome. "On the first 54 stimulated trials, the monkey chose the stimulated direction 51 times. It was utterly amazing; it was as if he couldn't help himself."

"This is the 'smoking gun,' " says Newsome. "This establishes the causality — the monkey is listening to these cells in order to make a judgment."

But is the monkey making a judgment, or is the electric shock driving the eye muscles more directly? Newsome believes the effect is indirect, as MT can be clearly defined as an area where sensations enter the brain, rather than an area that directly drives movement. There is also the issue of timing — the electrical stimulus is provided for as long as the dot display is on, but the monkey moves its eyes only once the dot pattern is turned off. (This is part of the training protocol developed in the absence of the electrical stimulus.)

Once Salzman and Newsome had worked out how to do the stimulation experiment, they could also ask how visual decisions are made in the face of conflicting information. As de-

THE OTHER HAND, WE HAVE BILLIONS OF NEURONS TALKING TO EACH OTHER.

Diagrams by Ian Worpole
MRI Image: Brian Wandell and postdoctoral fellows Heidi Baseler and Allen Poirson

scribed above, the dot display was shown moving in one direction, and a shock from an electrode in MT provided the conflicting information.

Possibly, as in areas of the brain that drive muscle movement, different signals are averaged, so simultaneous upwards and rightwards movements are interpreted as a diagonal direction both up and to the right. The researchers found, however, that MT uses a "winner-takes-all" strategy; the monkey chooses either directly up or directly to the right. This strategy allows the brain to keep two different objects separate, such as two cars crossing in opposite directions in front of a pedestrian. If MT averaged the motion of the cars, the pedestrian would not see any motion at all.

Vision — the beginnings

Vision research at Stanford started with a bang in the late 1970s with two major discoveries. Denis Baylor, MD, professor of neurobiology, knew that eyes were sensitive, but he wanted to know just how sensitive. He isolated pieces of retina, the tissue at the back of the eye that detects light, and measured the response of single cells to light. Amazingly, he found that a single cell could detect the smallest possible packet of light: a single photon.

Lubert Stryer, MD, was interested in how that light was converted into a signal in the cell. In black and white vision, light is detected when it hits a protein called rhodopsin. Stryer, also a neurobiology professor, found that rhodopsin passes the message on to another protein named transducin. And it did so repeatedly and rapidly; Stryer found that hundreds of copies of transducin were switched on within a second. "This is how you get the amplification of the single photon effect," says Baylor.

The linkage exemplified by rhodopsin and transducin turned out to be widespread in biology. Hormones and growth-stimulating factors use similar pairings, and in all cases the linkage amplifies the message.

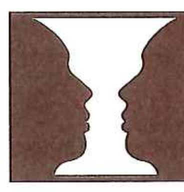
These experiments get at how the decision is made, but not where it is made. Only now can Newsome ask that question. "Now that we have a fine understanding of the sensory and motor sides, we can dare to look for what links the two," he says.

The activity of neurons in the decision area should reflect the monkey's interpretation of the dot pattern, not just the pattern of dots actually present on the screen. Thus, when the motion task becomes ambiguous, there will be a mixed signal in MT, but farther along the pathway, there should be a clear up or down signal corresponding to what is reported by the monkey.

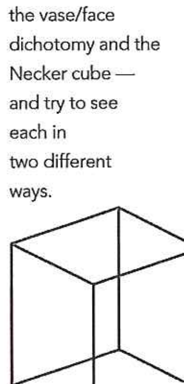
I don't have a way TO MEASURE CONSCIOUSNESS, SAYS NEWSOME. BUT WE'RE PROBABLY COMING AS CLOSE TO IT HERE AS ANYONE HAS EVER COME.

Even in MT there are signs of such activity. When the monkey is presented with pure noise — all the dots moving in random directions — it is trained to still guess up or down. There is a hint of a different signal in MT, depending on which choice the monkey makes.

The choice in response to the random snow pattern is a complete guess. But when presented with some simple scenes, people — and perhaps monkeys — really "see" the scene in one of two ways. The Necker cube or the vase/face dichotomy are two common examples: The cube comes out of the page or goes into the page, and there are two faces or one vase. But these interpretations never co-exist. There must, thinks Newsome, be an area of the brain that revs up or gears down whenever our interpretation changes from one to the other, even as the figure itself does not objectively change.



Look at these optical illusions — the vase/face dichotomy and the Necker cube — and try to see each in two different ways.



In ongoing studies with Andrew Parker, PhD, and Bruce Cumming, PhD, of Oxford University, Newsome has come up with a new visual scene for the monkeys. The scene, though conceptually similar to the Necker cube, uses moving dots. For the training period, the researchers give the monkey depth cues so that the scene can be interpreted in only one way. Later, they slip in ambiguous trials that can be seen either way. As the monkey flips from one interpretation of the figure to the other, it indicates what it is seeing with its eyes. The researchers, meanwhile, are on the lookout for neurons that switch on or off when the monkey changes its interpretation.

With this clear choice, it seems that activity in some parts of MT is actually a good predictor of the monkey's perceptual decision. And areas farther on in the visual pathway may be even stronger indicators of the monkey's perception.

The alternating interpretations of a Necker cube are not implicit in the lines on the page, but a construct of a conscious brain. If we understand the construction process, perhaps we are getting at the workings of consciousness.

Newsome is wary of such talk. The main problem is one of definitions, he explains. Most people are happy describing consciousness as brain activity a person has while awake rather than asleep. But what is that, exactly? At least three distinct levels of consciousness can be identified: perception of and reaction to information, conversion of that information into symbols that can be manipulated in our imaginations, and self-awareness, the fuzzy concept that describes our ability to think about ourselves.

Clearly, the monkey experiments do not get at self-awareness, the last of these categories. But perhaps they do cover the first, and maybe even the second.

The stumbling block that keeps Newsome quiet on consciousness is communication, or the lack of it. When the monkey looks at dots moving down and its "up" MT column is stimulated, it often reports that the dots move up. We presume that the monkey is experiencing something analogous to the moving cliff face next to the waterfall. But, asks Newsome, "if the monkey could talk to us, what would he say? Does he really see the world moving up? I really don't know." Perhaps the electrode drives the monkey to make a different choice, which its conscious mind knows is wrong. "I favor the first explanation," says Newsome, "but I don't see how I can know this, [as] I don't have a way to measure consciousness." Still, he says, "we're probably coming as close to it here as anyone has ever come."

The solution is to do the same experiment in humans. Such an experiment is not practical unless it can be done without electrodes in the brain, but with external sensors and stimulators. Newsome and Brian Wandell, PhD, a professor in Stanford's psychology department, hope to confirm the suitability of one external sensor — the magnetic resonance imaging (MRI) machine — by testing whether both MRIs and electrodes measure the same activities in monkeys.

But MRI measurements are slow, and they identify only millimeter-size blobs of activity, which are much larger than the MT columns. And the available external stimulators are crude. About them, Wandell says, with only a hint of exaggeration: "Basically you take a hammer and bang someone on the side of the head with it."

Somehow, says Newsome, the subjective has to be brought into objective science. Otherwise, speculations about consciousness will remain speculations. "The internal life is what matters," he says. "If science stops short of that, we've mined all the silver and left the gold in the tailings." SM