MIND ARCHITECTURE

Keep It in Mind

What is consciousness? A neuroscientist's new book argues that it arises when information is broadcast throughout the brain

Quantum physicist Wolfgang Pauli expressed disdain for sloppy, nonsensical theories by denigrating them as "not even wrong," meaning they were just empty conjectures that could be quickly dismissed. Unfortunately, many remarkably popular theories of consciousness are of this ilk—the idea, for instance, that our experiences can somehow be explained by the quantum theory that Pauli himself helped to formulate in the early 20th century. An even more far-fetched idea holds that consciousness emerged only a few thousand years ago, when humans realized that the voices in their head came not from the gods but from their own internal spoken narratives.

Not every theory of consciousness, however, can be dismissed as just so much intellectual flapdoodle. During the past several decades, two distinct frameworks for explaining what consciousness is and how the brain produces it have emerged, each compelling in its own way. Each framework seeks to explain a vast storehouse of observations from both neurological patients and sophisticated laboratory experiments.

One of these—the Integrated Information Theory—devised by psychiatrist and neuroscientist Giulio Tononi, which I have described before in these pages [see "Ubiquitous Minds"; Scientific American Mind, January/February 2014], uses a mathematical expression to represent conscious experience and then derives predictions about which circuits in the brain are essential to produce these experiences. [Full disclosure: I have worked with Tononi on this theory.] In contrast, the Global Workspace Model of consciousness moves in the opposite direction. Its starting point is behavioral experiments that manipulate conscious experience of people in a very controlled setting. It then seeks to identify the areas of the brain that underlie these experiences.

ONCE A MEMORY OR SENSORY INPUT IS LOADED INTO THE GLOBAL WORKSPACE, **COGNITIVE PROCESSES CAN MAKE USE OF IT.**

Stanislas Dehaene, the French cognitive neuroscientist at the Collège de France in Paris who has devoted much of his career to studying the psychology of consciousness, has just published a compelling book on his investigations into how the Global Workspace Model maps onto the brain.

The model derives from the realization that whenever we become conscious of something—whether a familiar face in a crowd or the voice of a stranger—we can retain what we perceive in our mind for a brief period. This perception can remain in this short-term memory storage, a kind of mental scratch pad, even after the face has disappeared or the voice has died away. Cognitive scientist Bernard Baars of the Neurosciences Institute in La Jolla, Calif., who came up with the Global Workspace Model, took his central insight from the early days of artificial intelligence, in which specialized programs accessed a shared repository of information, the blackboard. According to Baars, it is the act of broadcasting data from the blackboard throughout a computational system, whether cybernetic or biological, that makes it conscious. Consciousness is just brain-wide sharing of information that is in the memory buffer of the blackboard.

This neural buffer does more than process recent sensory inputs. It can also call up a memory from long ago and move it into the buffer. Once information is loaded into this workspace, a host of powerful cognitive processes can make use of it. The data can be sent off to a particular brain area that processes language—a language module—where this knowledge can be readied for sharing with other people by formulating a spoken explanation: "Guess who I just saw over there." It can also be forwarded to a planning module to be reasoned about, and it can be stored in long-term memory. The act of transmitting these data from the brain's memory buffers to its various functional modules is what gives rise to consciousness.

Unfortunately, this workspace has extremely limited capacity. At any one time, we can be conscious of only one or a few items or events, although we can quickly shift things into and out of con-

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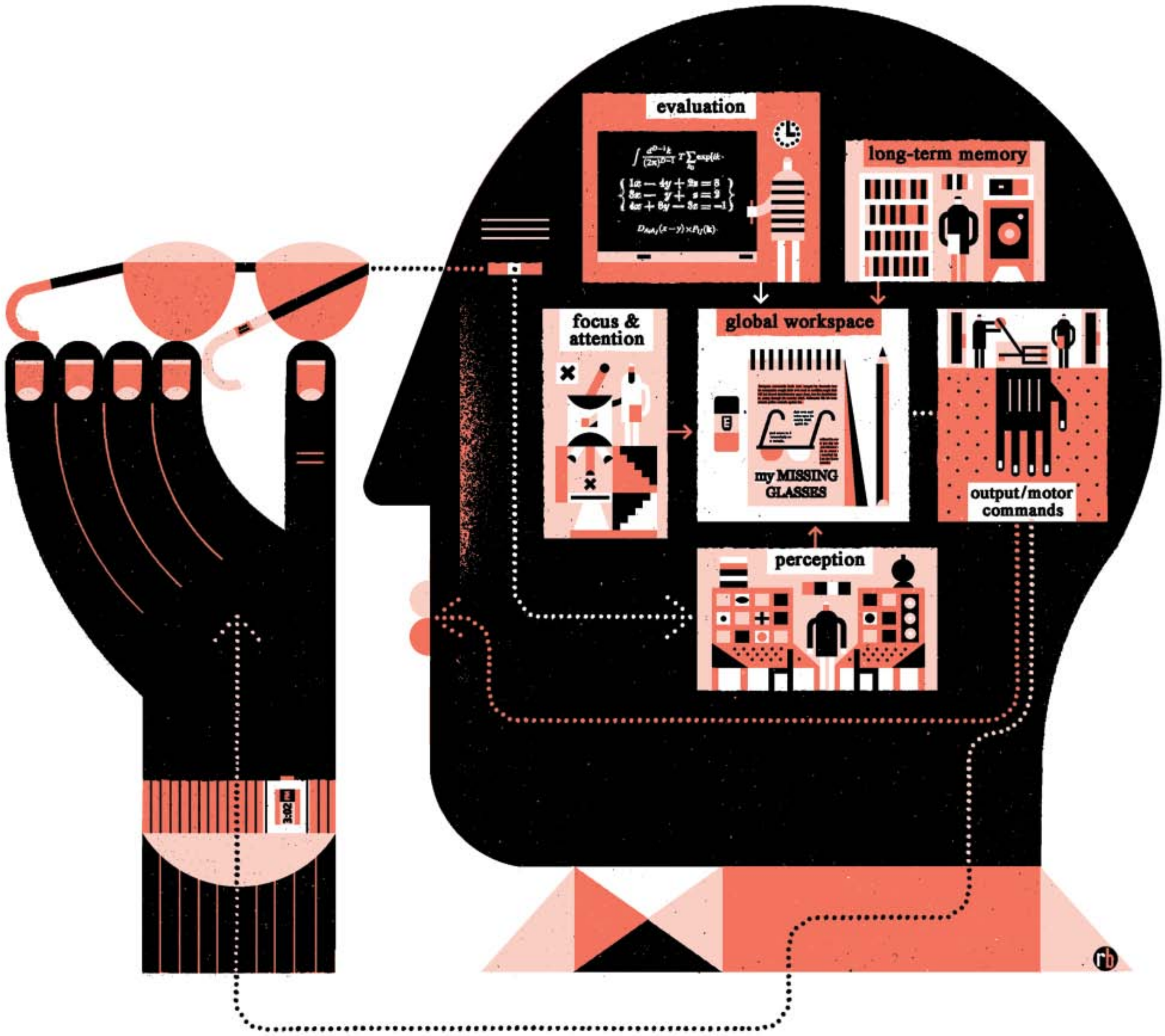

Cognitive scientists Stanislas Dehaene and Bernard Baars have suggested that memories, sensory perceptions, judgments and other inputs are stored in a type of short-term memory called the global workspace. This buffer gives rise to consciousness when the collected information is broadcast throughout the brain to stimulate cognitive processes that then engage the motor system, spurring the body to action.

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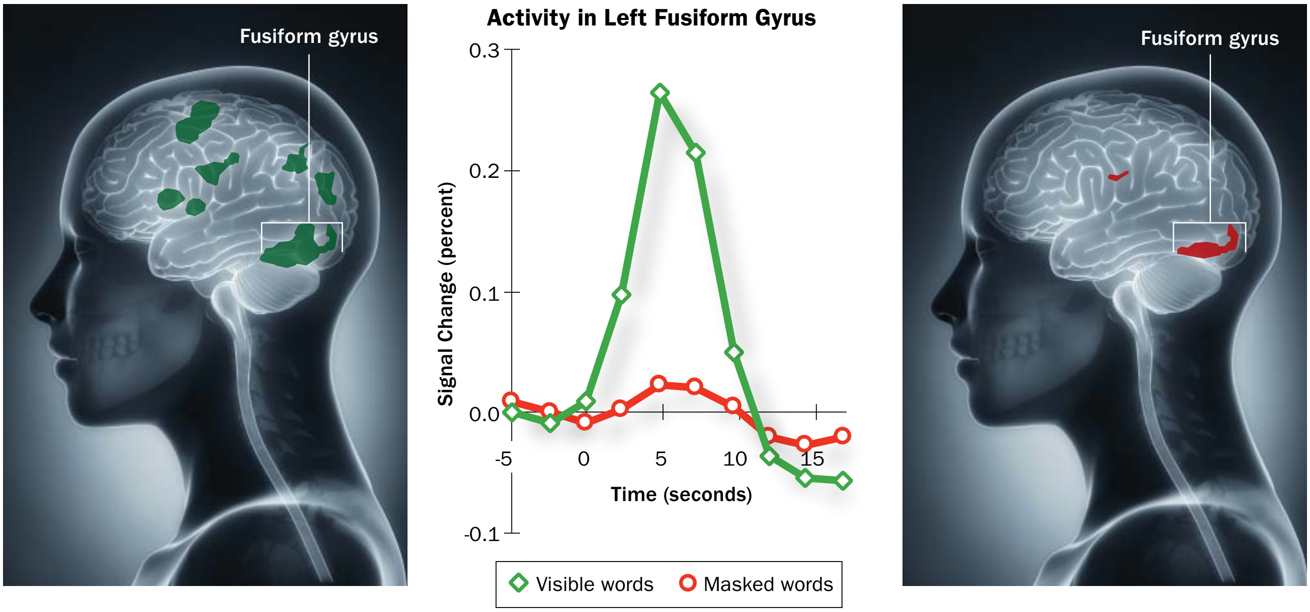
sciousness. New information competes with the old and may ultimately overwrite it. This limitation probably is an unavoidable design characteristic of any information-processing system that is overwhelmed by inflowing data streams and has to concentrate its most precious resources on dealing with a couple of critical items as fast as possible.

The brain compensates for the dearth of neural bandwidth by calling on a host of unconscious processes that either totally bypass this central scratch pad or interact with it below the level of awareness. The vast subliminal onslaught of data thereby turns sounds into meaningful words and photons into objects and identifiable people. These processes evaluate and weigh evidence, pass judgment and synchronize the movements initiated by the musculoskeletal system so that an organism can survive in a constantly and rapidly changing world. They are sophisticated and act quickly but do not share information with one another, nor do they transfer it into the common workspace. As with an intelligence agency, information is shared only on a need-to-know basis.

Yet these myriad agents of the uncon-



Presentation of a visible word to a viewer leads to a flurry of activity in many regions throughout the cerebral cortex—and in particular, the left fusiform gyrus, where words are processed (*left*). The activity is more than 10 times higher (*graph*) than if the displayed word is masked (*right*). The network of activated brain regions corresponds to the global workspace, a key set of neurons that are part of the brain's machinery for producing consciousness.

scious shape our daily routines. Because we have, by definition, no access to these subliminal events, we consistently underestimate their importance. Yet occasionally they manifest themselves quite dramatically. Japanese novelist Haruki Murakami put it well in a striking interview: "We have rooms in ourselves. Most of them we have not visited yet. Forgotten rooms. From time to time we can find the passage. We find strange things … old phonographs, pictures, books … they belong to us, but it is the first time we have found them."

Dehaene probes these unconscious lairs using a technique called masking. A picture, say, of a face or a word is briefly flashed onto a monitor, preceded and followed by images of a bunch of randomly drawn lines or a cloud of X's. These "masks" prevent the displayed face or word from becoming conscious—a subject reports seeing only a mask. Combining versions of this technique with recordings from electrodes implanted deep into the brain of patients monitored for epilepsy seizures, Dehaene and his colleagues demonstrated that the unconscious can process the meaning of word combinations—the brain responds differently to "happy war" than to "happy love"—implying that it has noticed the incongruence of having a word with a positive emotional meaning followed by a word with a negative one.

Dehaene and the distinguished molecular biologist Jean-Pierre Changeux have gone beyond this rather abstract model and are searching for the specific brain areas and populations of neurons that correspond to the global workspace. Their ongoing research using functional brain imaging and electroencephalographic electrodes placed on the skull has uncovered distinct neural signatures in these regions that appear to represent the theorized mental buffer.

In one classic experiment, Dehaene and his colleagues had volunteers lie inside a magnetic resonance imaging scanner while they watched a stream of words on a computer screen, each one displayed for 29 milliseconds. Some of the words were masked, which triggered only a slight brain response. But when the words were legible, an avalanche of neural activity occurred.

The activated regions make up a dense tapestry of interlocking brain cells—specifically pyramidal neurons—that tie to-

THE ACTIVITY OF A PARTICULAR BRAIN NETWORK IS THOUGHT TO EVOKE **A TELLTALE SIGNATURE OF CONSCIOUSNESS.**

SOURCE: "CEREBRAL MECHANISMS OF WORD MASKING AND UNCONSCIOUS REPETITION PRIMING," BY STANISLAS DEHAENE ET AL., IN *NATURE NEUROSCIENCE*, VOL. 4, NO. 7, JULY 2001; THINKSTOCK (*heads*) gether the prefrontal cortex, the inferior parietal lobe, the middle and anterior temporal lobes and other brain regions. Axons, the wirelike extensions from a neuron's cell body, fan out from the brain's fissured surface, the cerebral cortex, to bind together vast reaches of neural topography. This network is where Dehaene and his colleagues have started to look both for the brain's scratch pad and for how signals streaming through this web of connections are communicated to the rest of the brain.

Whenever a stimulus is consciously perceived, its neuronal footprint—a particular type of brain activity—shows up in many parts of the cerebral cortex. Take, for instance, the intense electrical activity triggered by an image that passes into the primary visual cortex at the back of the head and from there to many cortical regions. As it reaches anterior regions of cortex, the signals increase in amplitude, prompting Dehaene to call it a neuronal avalanche.

The intense neuronal firing can be caught in the act with EEG electrodes by measuring the P300 wave, a brain wave that, in experiments, starts about 300 milliseconds after an image is projected onto a computer screen. As Dehaene's experiments demonstrate, becoming conscious of a sight or sound by having it broadcast throughout the brain to areas postulated to make up the global workspace often goes hand in hand with the presence of a P300 wave in the prefrontal cortex, a brain area associated with higher mental processes. Conversely, without the signature P300 wave, electrical activity dies out, and the image displayed is not consciously perceived. The information fails to enter the global workspace and so remains subliminal.

First Glimmers

Dehaene and his colleagues used this electrophysiological marker of conscious perception to map when consciousness first arises in five- to 15-month-old infants [see "The Conscious Infant"; Scientific American Mind, September/October 2013] and to devise a clever test for consciousness in severely brain-injured patients with whom no reliable communication using speech, eyes or gestures is possible. The tests depend on the ability of a conscious individual to detect a novel stimulus—imagine reading a book when your cell phone abruptly rings. This unexpected event can trigger a massive P300 wave that is readily noticeable. Yet when you do not pick up the phone and it rings again and again, you come to expect it, and the P300 becomes fainter until it cannot be detected.

In the laboratory, the researchers play a sequence of five simple tones: *beep beep beep beep boop*. The last odd-man-out tone generates a strong P300. When the entire sequence of five tones is repeated three times, the brain adapts to the deviant sound, and the consciousness marker disappears.

Then, along comes a *beep beep beep beep beep* sequence. As an attentive subject becomes conscious of the lack of a deviating sound in the fourth sequence, her brain responds with a P300 to the final *beep* because it was conditioned to expect a *boop*.

Preliminary trials using this test with brain-injured patients are intriguing. Patients in whom behavioral evidence indicates a minimal level of consciousness show this pattern of P300 activity on their EEGs, whereas those in a coma, thought to be without any sensation whatsoever, do not. Ongoing experiments seek to exploit the same odd-man-out paradigm in monkeys and in mice.

Proposing that what we consciously experience can be defined as the brain's ability to distribute information from the global workspace to the rest of the brain brings up several questions. Why and how, for instance, does broadcasting information from the global workspace give rise to consciousness? What message is being broadcast? Blood-borne hormones and chemicals that regulate neural activity also relay information throughout the body and brain. Yet we are not aware of them. Why not? And can data transmitted over the Internet or information coursing through the nervous system of a roundworm represent conscious activity? For now the Global Workspace Model avoids such thorny questions.

CONSCIOUSNESS AS A FORM OF BROADCAST TV **RAISES A SERIES OF UNANSWERED QUESTIONS.**

When the molecular-biologist-turned-neuroscientist Francis Crick and I started our joint work in the late 1980s on trying to understand the brain activity underlying vision and other mental processes, scant experimental work was dedicated to empirical studies of the hallmarks of consciousness.

As the work by Dehaene, Changeux and their colleagues makes abundantly clear, this sorry situation has changed radically. Their research program is beginning to untangle how the firing of networks of brain cells translates into this most mysterious of all phenomena. **M**

FURTHER READING

- **Experimental and Theoretical Approaches to Conscious Processing.** Stanislas Dehaene and Jean-Pierre Changeux in *Neuron,* Vol. 70, No. 2, pages 200–227; April 28, 2011.
- **Consciousness and the Brain: Deciphering How the Brain Codes Our Thoughts.** Stanislas Dehaene. Viking Adult, 2014.