How the brain decides what to focus conscious attention on

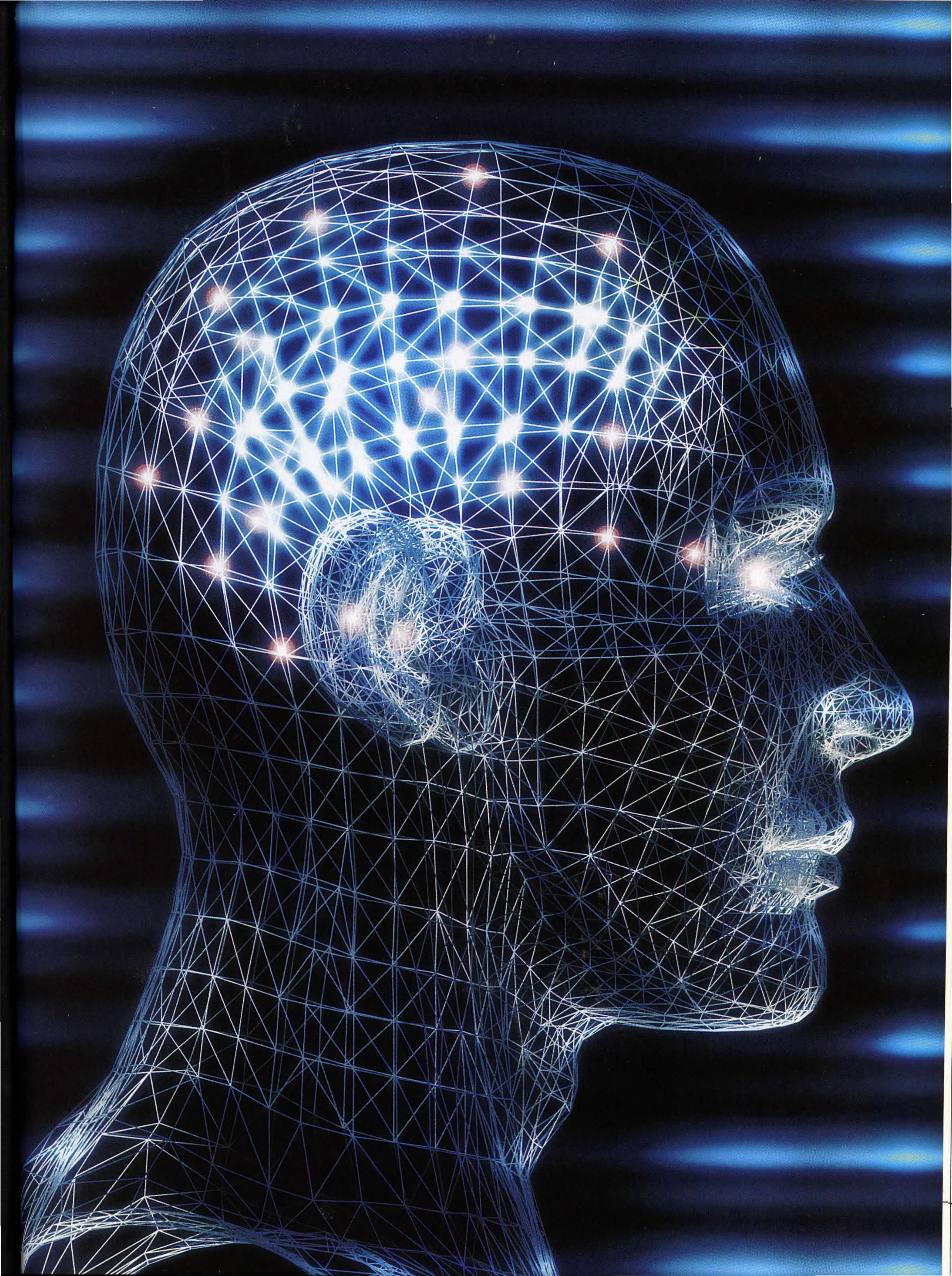
Coming to ATTENTION

By Andreas K. Engel, Stefan Debener and Cornelia Kranczioch

With an impish smile, the professor announced that he was about to carry out a little experiment. He asked his class to watch a short video of two basketball teams and to count how many times the players in white T-shirts passed the ball. The students found that it wasn't easy to keep their eyes on the moving ball, but most of them believed they counted correctly.

After the show, the teacher turned to face everyone again: "What did you think about the gorilla?" There was a shocked silence. He restarted the video, and after a few seconds a collective groan rippled through the room: as the audience now realized, a person in an ape costume had walked right across the court, pausing in the middle to pound on his chest.

Psychologists Daniel J. Simons and Christopher F. Chabris showed this film at Harvard University for the first time in 1999. They were surprised by the results: half the observers missed the furry figure the first time they watched. How was that possible?



(What happens in our brains when we deliberately **concentrate** on something?)

As cognitive neuroscientists, we would like to know what is behind such phenomena: What happens in our brains when we deliberately concentrate on something? Does some mechanism inside our heads decide which information reaches our consciousness—and which does not? And do our intentions, needs and expectations influence what we perceive? Recent research offers some fascinating insights.

Homing in on Attention

Psychologists began seeking answers to such questions as long ago as 1890, when American philosopher and psychologist William James wrote about important characteristics of attention in *The Principles of Psychology*. James concluded that the capacity of consciousness is limited, which is why we cannot pay attention to everything at once. Attention is much more selective: it impels consciousness to concentrate on certain stimuli to process them especially effectively. James and others also distinguished between types of attention. Some of them are "self-created": a penetrating odor, a loud siren, a woman in a bright red dress amid people clad in black. (Many researchers now call this process "bottom-up," because the stimuli battle their way into our consciousness automatically because they are so striking.) Alternatively, we can actively and deliberately control our focus (called "top-down," because higher brain regions are involved at the outset). For example, at a noisy party, we can tune out background noise to listen to the conversation at the next table.

Neuroscience did not take up this topic until much later. In 1985 a research team led by Robert Desimone at the National Institute of Mental Health was first to observe how single neurons in the visual cortex of rhesus monkeys changed their activity depending on what the primates were looking at. Desimone and his collaborator Jeffrey Moran discovered that certain neurons in the V4 area of the visual cortex—an area important for the perception of color—fired more frequently when the test animal gazed fixedly at a colored target. The same nerve cells exhibited much weaker activity when the ape noticed the target but did not look right at it. Other researchers later discovered that active attention was not only reflected in the higher levels of visual processing, such as in the V4 area, but could also be traced down to stimulus processing in the lowest levels in the cortical hierarchy.

Synchronous Firing

All these studies linked attention to an increase in the firing rate, or activity, of neurons. Now the latest neurobiological research points to another significant factor in attention: huge numbers of neurons synchronize their activity. Many neuroscientists believe that study of this phenomenon will provide the answer to one of the biggest riddles of attention research, the so-called binding problem.

Imagine that a grasshopper suddenly lands on the table in front of you. Before the insect can arrive in your consciousness as a fully realized, three-dimensional entity, several different areas

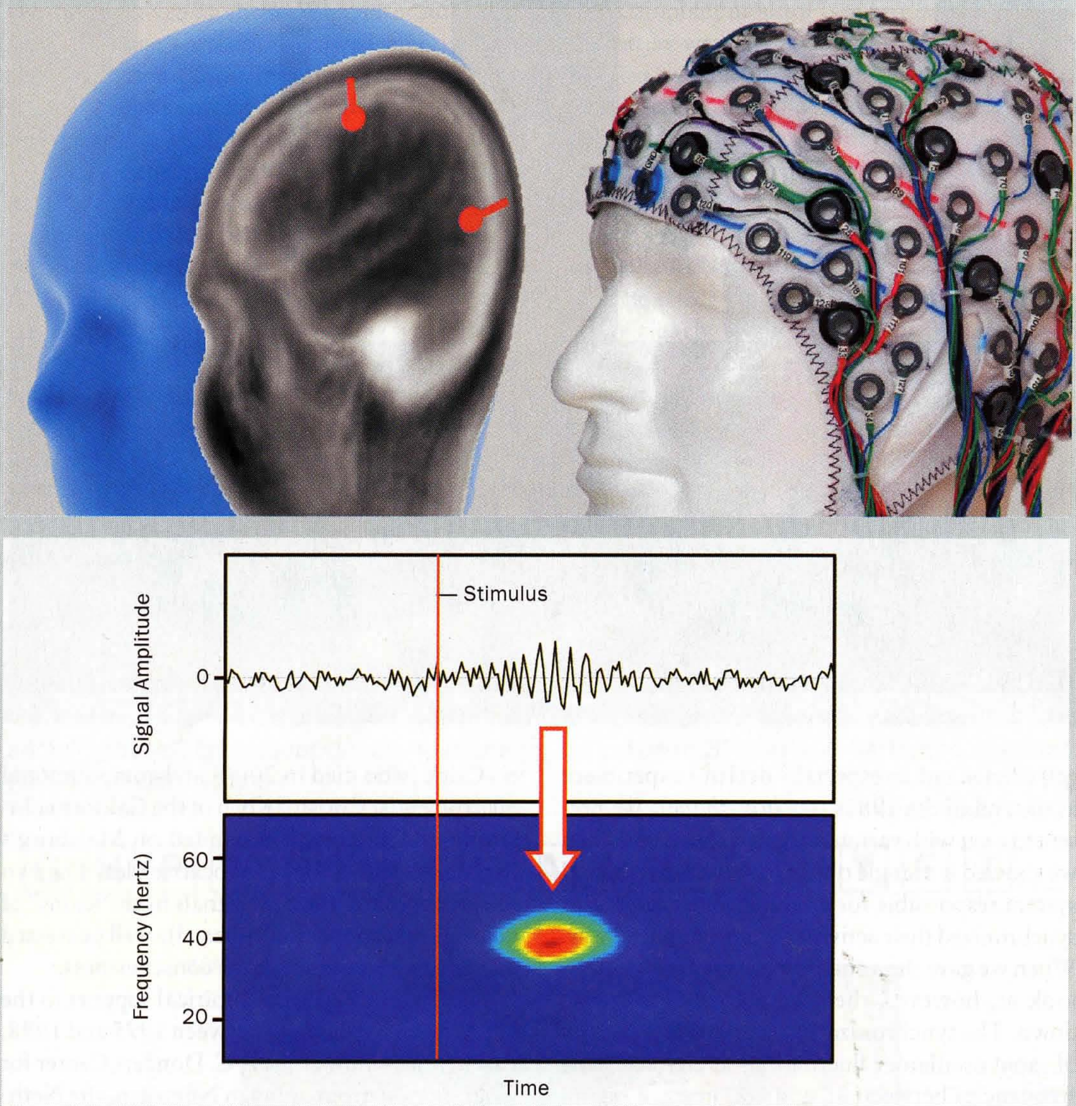
Follow the Ball

Ask a friend to count the number of passes by the team wearing white shirts in the video at http://viscog.beckman.uiuc.edu/djs_lab/demos.html (but don't warn him about the ape). He probably will not notice the interloper.

GETTY IMAGES (*preceding page*); "GORILLAS IN OUR MIDST: SUSTAINED INATTENTIONAL BLINDNESS FOR DYNAMIC EVENTS," BY D. J. SIMONS AND C. F. CHABRIS, IN *PERCEPTION*, VOL. 28, NO. 9, PAGES 1059–1074; 1999. COURTESY OF DANIEL J. SIMONS (*this page*)

Nerve Cells in Synchrony

Active regions in the brain generate electrical signals that electrodes attached to the scalp can read (*top right*). After recording EEG measurements using many electrodes, scientists can reconstruct the originating location of the signals using mathematical methods (*top left*). Sensory stimuli lead to oscillatory responses in the EEG (*top graph*), which are the result of synchronous activity by many neurons. The frequency distribution of the measured signal can be examined for each electrode, and the change in this frequency distribution during the time after presentation of the stimulus is represented. Warm color tones indicate an increase in activity in the time-frequency region of interest (*bottom graph*).



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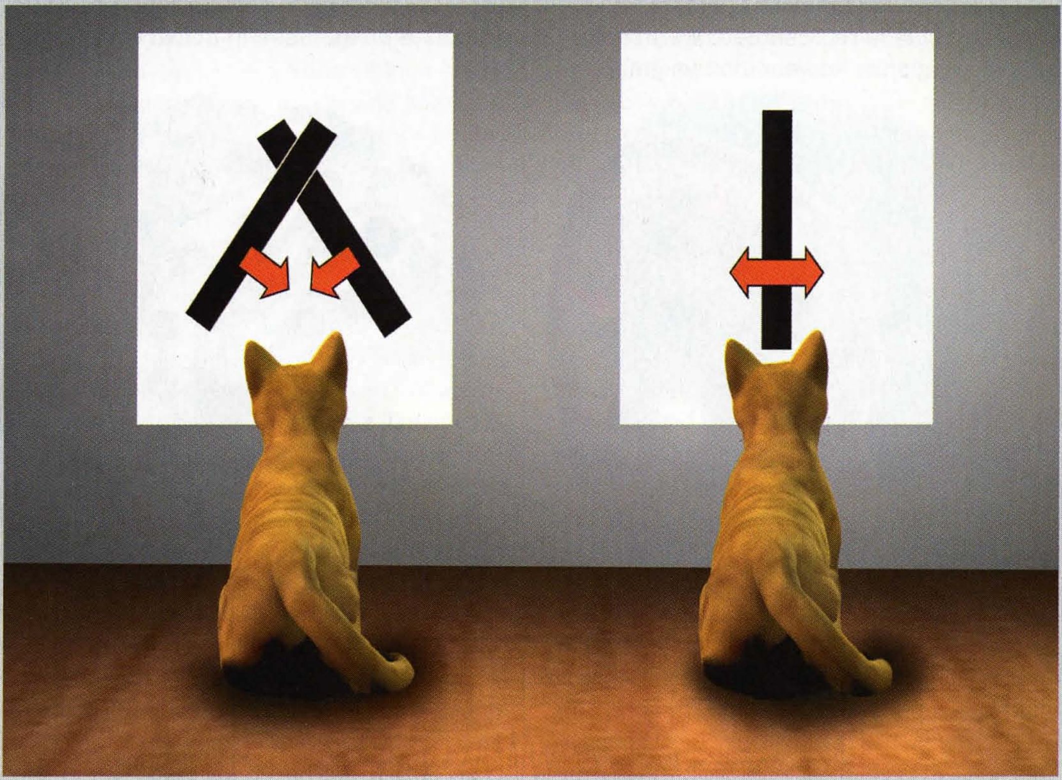
of the brain must be active. One processes the insect's color, another its size, yet another its location, and so on. How does the brain bind all these individual characteristics together into a single impression of a green grasshopper?

Twenty years ago Christoph von der Malsburg, a computer scientist and brain theorist, now at the Ruhr University in Bochum, Germany, suggested a solution. By synchronizing their activities, nerve cells could join into effectively cooperating units—so-called assemblies. Subsequently, a number of research teams, among them the group at Wolf Singer's laboratory at the Max Planck Institute for Brain Research in Frankfurt, have demonstrated that this "ballet of neurons" in fact exists. Peter Koenig, Singer and one of us (En-

Cats with a Binding Problem

At the left in this schematic representation, a cat perceives two targets moving in different directions (*arrows*) across a screen. One group of directional neurons in its visual cortex reacts to the movements of one target, a second to those of the other. Both nerve cell populations fire independently of each other. But the groups synchronize their activity when they look at the vertical target in the right image, which moves to the left or right (*arrows*).



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gel) carried out an especially decisive experiment at the end of the 1980s [*see box above*]. We presented a cat with various targets to observe. When we showed it a single object, neurons in its visual system responsible for analyzing characteristics synchronized their activities in a pronounced way. When we gave the animal two separate objects to look at, however, the common rhythm broke down. The synchronization changed to a pattern of rapid oscillatory fluctuations at characteristic frequencies between 30 and 100 hertz, a region that brain researchers call the gamma band.

Then, in the early 1990s, Nobel laureate Francis Crick (who died in 2004) and computational neuroscientist Christof Koch of the California Institute of Technology expanded on Malsburg's hypothesis with a then provocative idea. The two scientists posited that only signals from "teams" of neurons that cooperated especially well possessed enough strength to reach the consciousness.

Recent findings lend empirical support to the Crick-Koch hypothesis. Between 1995 and 1998, Pascal Fries—now at the F. C. Donders Center for Cognitive Neuroimaging in Nijmegen, the Netherlands—and Singer, Engel and others at Max Planck carried out some of these experiments. The investigators took advantage of an effect called binocular rivalry: if the right eye and the left eye are equipped with special glasses that let each see only one of two very different images, the subject cannot meld them into a single perception. The brain resolves this dichotomy by favoring input from one eye and suppressing input from the other. As a result, the volunteers always saw just one

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of the pictures at a time. First they would see one image and then, a few seconds later, the other.

Two Eyes Vying

How is binocular rivalry waged at the neuronal level? We compared two groups of nerve cells in the visual cortices of cats: one group dealt with the characteristics of the left image, the other with those of the right. From an animal's behavior we could tell which image it was looking at during any given moment. Whichever side occupied the feline's attention showed superior neuronal synchronization. In contrast, when we then compared the neurons' firing rates, we observed no difference. This result demonstrated that the degree of neuronal synchronization decisively influences which incoming signals are further processed and thus becomes relevant to the consciousness's perception.

Fries also showed that active, intentional control of attention can influence gamma synchronization. He worked in Desimone's lab with macaques that had learned to direct their attention to a particular spot on the monitor screen in response to a signal; a stimulus would appear at that location after a short delay. If this stimulus appeared at the expected location, the gamma oscillations were clearly stronger. Synchronization immediately weakened, however, as soon as the research animals switched their attention to other stimuli.

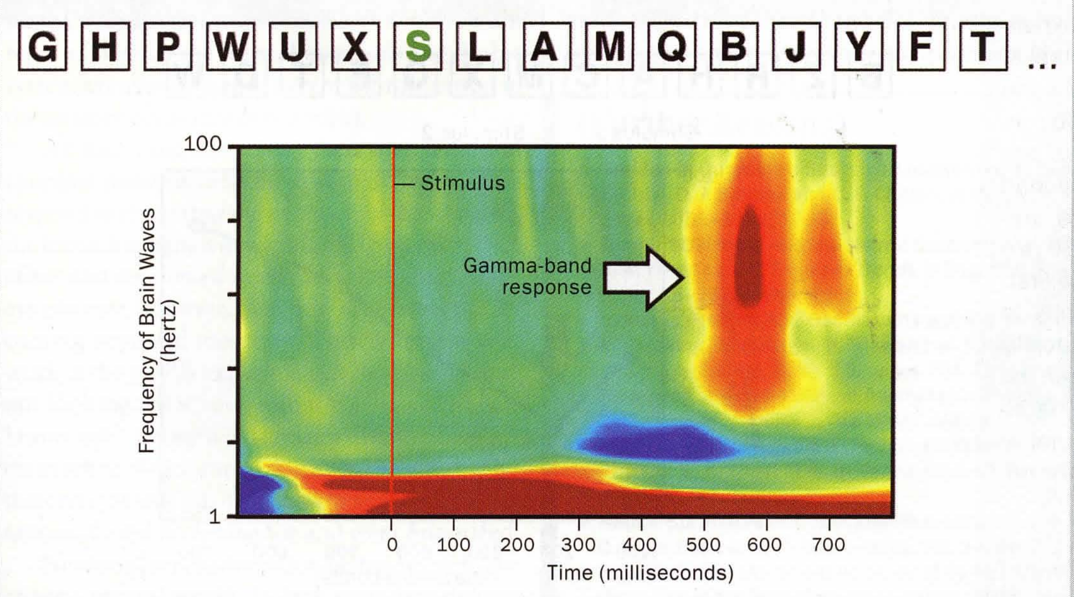
For humans, such experiments using implanted electrodes are possible only during brain surgery. As a result we usually measure gamma activity by means of electroencephalography (EEG). We recently carried out an attention experiment in which subjects read letters that flashed briefly on a computer monitor [*see box below*]. Most of the letters were black, but now and again we inserted a few green letters, which we asked the subjects to count. Analysis of the EEG signals taken during the tests showed that only the unexpected appearance of green letters produced an increase in the high-frequency part of the gamma band.

Expectant Neurons

The effect of expectation reveals itself especially clearly in an experiment using acoustic stimuli. We asked listeners to pay particular attention to high tones in a series of more or less similar tones. When they heard the target tone, a high-frequency gamma-band activity appeared in the brain; in contrast, unexpected loud noises,

Letter by Letter

When test subjects focus attention deliberately, an EEG can read especially rapid brain waves. If the volunteers are asked to count green letters that appear among a series of black letters, the stimuli arouse high-frequency activity in the region between 30 and 100 hertz, the so-called gamma-band response.



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which automatically call attention to themselves, did not elicit this effect.

Regardless of which sensory system is involved, the reinforced rhythmic synchronization in the gamma band that we measured seems to be a good indicator of active attention. When a person deliberately directs attention to a stimulus, not only do the firing rates of individual neurons in the brain change, but the synchronization also improves for all the neurons taking part in the coding for the same stimulus. We liken the effect to a symphony orchestra that soon arrives at a common tempo after the individual instruments begin playing.

In what ways might intentions and needs influence attention? With the help of functional magnetic resonance imaging (fMRI), we wanted to locate brain regions involved in conscious perception of a target stimulus. To do so, we needed a research technique to compare two conditions: one that led from active attention to conscious awareness of a stimulus, and a second, in which the same stimulus did not penetrate the consciousness. We used a phenomenon called attention blink. In the experiment we once again displayed a series of letters to subjects while we observed them with fMRI. This time, however, only a single green letter appeared among rapidly changing black letters, and the subject had to tell us, at the end of the test run, whether or not it was a vowel. At the same time, the subject was to look for a black X that popped up at different times after the green letter.

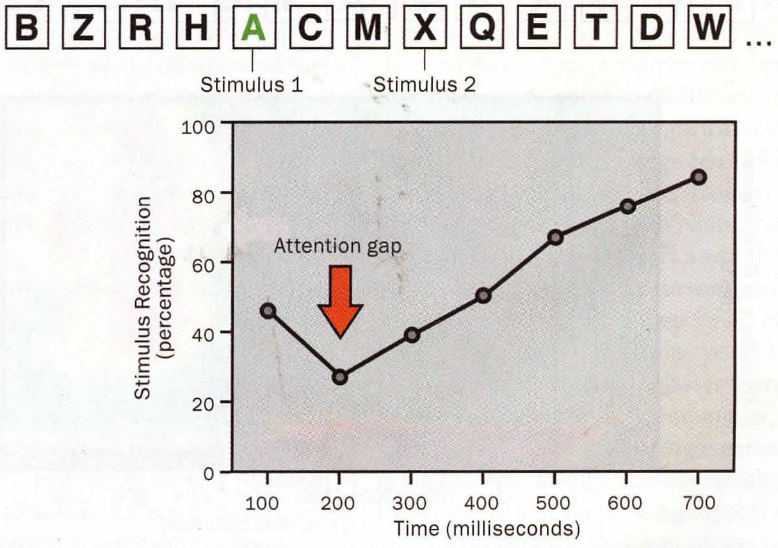
During the experiment, the attention of our subjects showed clear gaps—the "blinks"—as a result of their intentional, conscious focus on the task [*see box below*]. If the black X appeared very soon—within a third of a second—after the green letter, about half the time the participants did not notice it. If there was a longer period after the first stimulus, their recognition rate improved.

At the end of the experiment, we compared the fMRI values for each run-through in which the subjects perceived the X with those in which it was shown but not noticed. We saw clear differences in activity in a few brain regions, all in the frontal and the parietal cortices. Scientists have been aware of these regions' importance in controlling attention for a long time: for example, some patients who suffer damage to certain parts of their parietal cortex from a stroke can no longer pay attention to any stimuli in certain areas of their visual fields, which means they cannot consciously perceive them. We were surprised, however, when we found a difference in the limbic system—in the amygdala, to be precise, which is normally involved in processing emotional reactions. The state of our emotional system probably influences the control of attention and which sensory signals are allowed to reach consciousness.

The experiments we describe provide another puzzle for researchers who are seeking the neuronal basis of consciousness: the gamma oscillation that is closely associated with conscious percep-

The Mind's Eye Blinks

If subjects in an experiment receive two tasks, one coming very soon after the other, their attention capacities are strained. If the second stimulus comes between 200 and 300 milliseconds after the first, the subjects' ability to recognize it is especially weak. It is only when the two stimuli are separated by larger time intervals that they can be noticed reliably.



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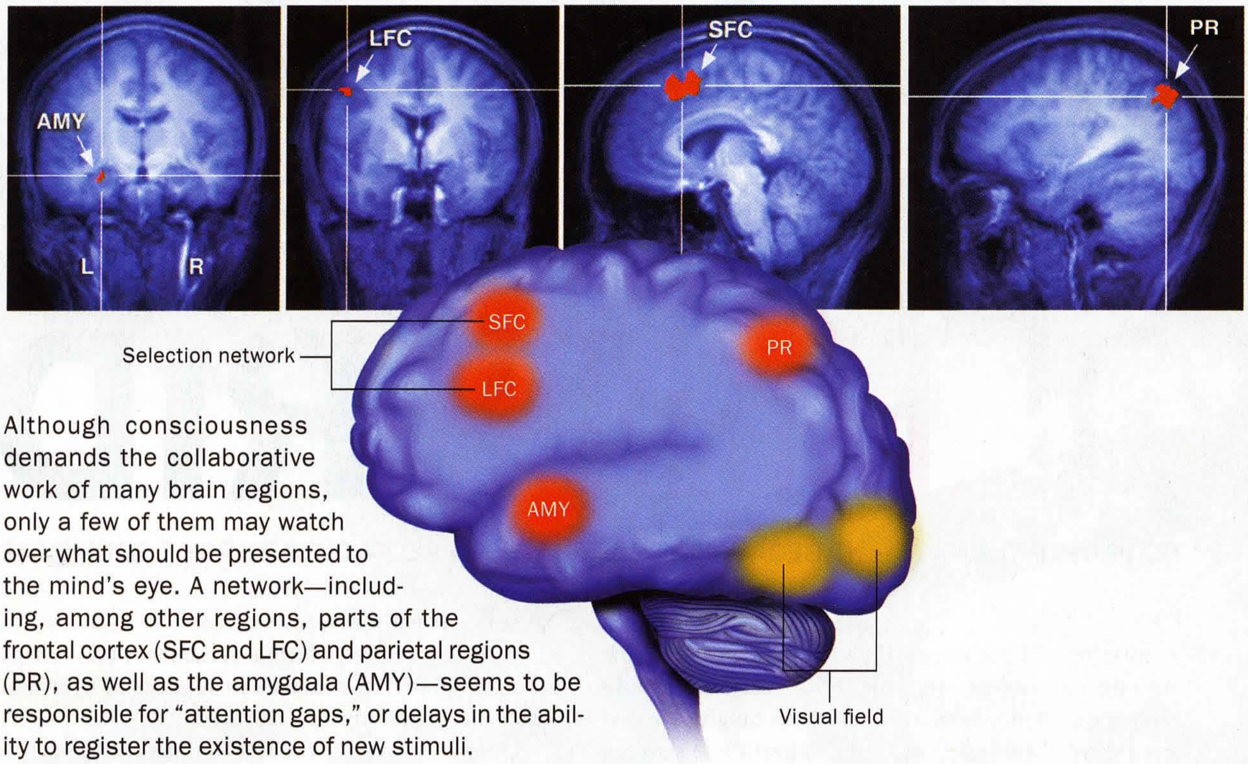
Neuronal Puppet Master



Although consciousness demands the collaborative work of many brain regions, only a few of them may watch over what should be presented to the mind's eye. A network—including, among other regions, parts of the frontal cortex (SFC and LFC) and parietal regions (PR), as well as the amygdala (AMY)—seems to be responsible for "attention gaps," or delays in the ability to register the existence of new stimuli.

SIGANIM *Gehirn & Geist*, AFTER ANDREAS K. ENGEL, STEFAN DEBENER AND CORNELIA KRANCZIOCH

tion does not just depend on external stimuli but also on the flexible inner dynamic of the brain. We theorize that neurons are constantly and actively predicting where the visual stimuli they expect will appear. Fries and other researchers have in fact measured the synchronization effect in the visual area of animals even before they were presented with an expected stimulus. Probably, brain regions such as the frontal cortex or the limbic system exercise influence over synchronization in the sensory areas [*see box above*].

All incoming stimuli set their own temporal coupling patterns in motion. If these stimuli correspond to those that the expectation has created, the incoming signals are reinforced by a resonance effect and conducted onward. If the expectations are not met, however, the brain suppresses the incoming neuronal messages. This process was at work in the gorilla experiment. The subjects were not looking for a person in a gorilla suit. Their brains were engaged in tracking the moving players in white. Any information about an ape that hit their retinas was out of sync with neuronal expectations, found no resonance and went unnoticed.

Neuronal synchronization brings order to the chaotic mental world. In fact, cognitive deficits and disordered thoughts among schizophrenic patients appear to be connected to disturbed gamma-band coupling. The healthy brain is, however, anything but a passive receiver of news from the environment. It is an active system, one that controls itself via a complex internal dynamic. Our experiences, intentions, expectations and needs affect this dynamic and thus determine how we perceive and interpret our environment. **M**

(Further Reading)

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