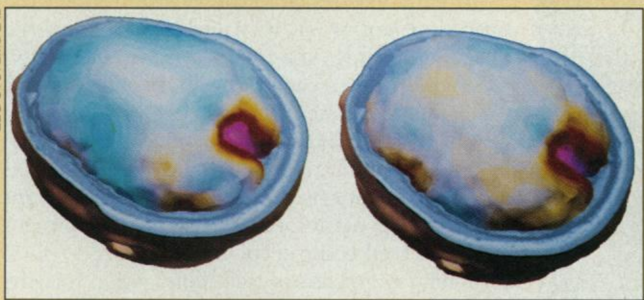
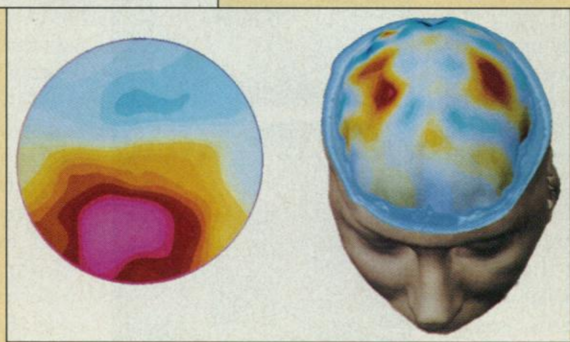
EEG + MRI: A Sum Greater Than the Parts

One goal of biomedical imaging is to "see" biological processes taking place. The most complex of those activities is, of course, thinking. And while it might seem like dreaming to imagine seeing the brain in action, it isn't. In fact, by combining magnetic resonance imaging (MRI) with electroencephalography (EEG) it is now possible to study how the cortex coordinates its actions to produce thought. Using this combination, "for the first time, we can actually watch the higher brain at work in real-life situations," says Alan Gevins, a neuroscientist and president of EEG Systems Laboratory, a nonprofit research institution in San Francisco.

EEG SYSTEMS LAB





Summing up. The disc at right is a conventional two-dimensional EEG map of brain function. The others are three-dimensional maps made by combining MRI and EEG data.

Adds Robert W. Thatcher of the University of South Florida College of Medicine in Tampa, "We're no longer looking at brain function in terms of indirect measures such as blood flow or energy metabolism, but in terms of the electrical activity of neural networks." And that is making it possible to check the accuracy of neural network models developed on computers, which could push neuroscience a big step forward.

Unlike many of the other advances described in this *Science* special report, seeing the brain at work isn't the result of a stunning new technique. EEG has been around for more than 60 years as a means of measuring the brain's electrical signals. Yet its usefulness has been limited because those signals diffract (bend) as they pass through the skull, blurring the image and limiting the amount of spatial information that can be obtained. But Gevins, working with a number of collaborators, has developed mathematical models that exploit MR data from skull images to solve the diffraction problem. The MR data also provide a high-resolution map upon which they can superimpose the improved EEG data.

Using MR to "correct" EEG sounds logical, but it wasn't easy. Gevins says it took 5 years of work by an interdisciplinary team including mathematician Jian Le, also of EEG Systems Laboratory, to develop the algorithm that converts MR data into a "finite element" electrical model of the brain, skull, and scalp. Supercomputer-based finite element models, which use networks of discrete, finite volumes to represent larger entities, are used to model complex systems, but to make the method useful, it must be able to run on widely available computers. Le's breakthrough lay in creating a model that would integrate MR data and 128-electrode EEG recordings—and run on a computer workstation like those found in most labs.

Using this new setup, Gevins and his collaborators at the Air Force School of Aerospace Medicine and Washington University have been studying information processing in the brain. In one set of experiments, the researchers studied "working memory," the activity that enables us to retain data needed to perform an ongoing task, for example, holding a telephone number in the mind while dialing.

Test pilots, fitted with an EEG electrode array, sat in front of a video display watching a stream of numbers that they had to remember; when a new number appeared on the video screen the subjects had to make a finger pressure response proportional to a number seen 12 seconds earlier. Before the next number appeared, many centers in the brain, including regions in the premotor and left posterior parietal cortex, began communicating. For the first 6 hours, there was no change in activity patterns seen with each replication, but as the sessions wore on, the patterns changed and grew weaker as the pilots became fatigued. Interestingly, the patterns changed well before there was any noticeable dropoff in performance on the memory test.

Thatcher, who until recently was at the National Institute of Neurological Disorders and Stroke (NINDS), adds another twist to the combination of MR and EEG: positron emission tomography (PET). PET data are used to calculate electrical dipoles in the cortex during mental activity. "The appearance and disappearance of dipoles give us a picture of how neural networks couple and decouple during mental activity," said Thatcher. The PET data, which provide accurate spatial detail of brain activity, serve to validate computational models for dipole positioning based on MR and EEG data alone, and they will be discarded as confidence in MR-EEG models improves.

Using this method, Thatcher and colleagues C. Toro and M. Pflieger, at NINDS, and M. Hallett at Neuroscan Inc. in El Paso, Texas, observed neural networks in the brain prepare for activity. Subjects fitted with a 29-electrode EEG were asked to raise an index finger approximately every 4-5 seconds. About 200 milliseconds prior to each movement, neural networks would spring into action and couple—each coupling shows up as a dipole—but as soon as the movement started, most of these networks decoupled. According to Thatcher, the most surprising finding was that the coupling and decoupling were not instantaneous. "With a computer, you turn a switch on or off and you get an all or nothing response, but in the brain we're seeing that there's inertia in these connections. It takes a finite time to set them up and a finite time, many milliseconds, to shut them down," he said.

Experiments such as these, says Thatcher, are the first steps toward answering one of the most important questions in neuroscience—how the brain coordinates activity to produce consciousness. One criticism of neural network models has been that there is no way to tell whether they reflect what is actually going on in the brain. But "with these imaging techniques we can finally move from modeling networks on computers to seeing them in action in a living, functioning brain," says Thatcher.

–J.A.