

NEUROBIOLOGY

Neurons Tap Out a Code That May Help Locate Sounds

The brain is a history of past experiences, as well as a computer, weighing data and plotting our next move. But it's also an atlas: The cerebral cortex contains a collection of neuronal maps showing where sensations come from. If you cut your left index finger, for example, your brain registers the location of the hurt by firing neurons in the part of the map of skin surfaces corresponding to that finger. If someone throws you a ball, you know where to reach out to catch it, because neurons in the appropriate part of the brain's visual map register the ball's approach.

The brain is also skilled at pinpointing sounds, but so far researchers looking for a spatial map in the auditory cortex—the brain area responsible for sound perception—have come up empty-handed, prompting speculation that the brain may have other tricks for registering the location of sounds. Now, John Middlebrooks and his colleagues at the University of Florida Brain Institute may have confirmed those speculations. On page 842, they report their finding that neurons in the auditory cortex convey information about a sound's location not by the neurons' spatial arrangement, but by their temporal pattern of firing. In effect, the brain may be tapping out the location of a sound in a neuronal equivalent of Morse code. That possibility is "what makes the paper interesting," says auditory neuroscientist Eric Young of Johns Hopkins University in Baltimore. "The higher auditory system, where sound perception probably happens, doesn't seem to have a map of space....So we are looking for other ideas."

From the beginning of his career, Middlebrooks has been on a quest for auditory maps. In the early 1980s, he worked as a postdoc with Eric Knudsen at Stanford University. Knudsen and Mark Konishi of the California Institute of Technology had already found a map of auditory space in the barn owl. That map, however, wasn't in the auditory cortex but in the superior colliculus, a part of the brain stem that controls the reflex by which the owl turns its head to face a sound. Middlebrooks found a similar map in the superior colliculus of cats; the combined findings led him to conclude that "the brain apparently knows how to make a [sound location] map."

As a reflex center, however, the superior colliculus has little or no role in perception, and the next step was to move to the cerebral cortex, where sound location is consciously perceived. A number of groups, including

Middlebrooks', searched the cerebral cortex for telltale signs of an auditory map—and failed. What they were looking for was a pattern of neurons in a grid, each firing electrical impulses in response to sounds from a particular location and remaining silent when the sounds came from elsewhere. Instead, Middlebrooks found that the neurons in an area of auditory cortex called the anterior ectosylvian sulcus (AES) fired off similar

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Neural explorers. John Middlebrooks (seated, left), along with Li Xu and Ann Clock (standing) and David Green, related neuronal firing patterns to sound locations.

numbers of impulses (known as "spikes" for their appearance on an oscilloscope) regardless of the source of the sound.

Musing over his data, Middlebrooks made a discovery. "Even though spike count didn't seem to vary reliably with sound location, I could see changes in the pattern of the spikes," he says. "There was some order there." Depending on where the sound came from, the spikes might begin earlier or later; their frequency also seemed to change.

Middlebrooks wasn't the first to conclude that information may be contained in the timing pattern of spikes. In 1987, Barry Richmond of the National Institute of Mental Health and Lance Optican of the National Eye Institute reported that some neurons in the visual cortex seem to record information that way. That information probably isn't necessary for recording location, since the visual system has its own spatial maps.

But the auditory cortex doesn't, and Middlebrooks postulated that differences in neuronal firing patterns might code for spatial location of sounds. To see if they do, Middlebrooks, working with postdoc Ann Clock, graduate student Li Xu, and psychophysicist David Green, used a computer-simulated

neural network designed to recognize patterns. They made electrical recordings from individual AES neurons in the brains of anesthetized cats while they moved a sound source to different spots in a 360-degree arc around the cats' heads. In each trial, they trained the network by feeding it firing patterns from an individual neuron as well as information about which sound location had produced each pattern. Finally, they tested whether the network could tell from patterns alone where a sound came from.

It could: The neural net located the sound sources more than twice as reliably as would be expected by chance. A cat's brain does much better, of course, but it also has many more neurons to listen to. "No single neuron is going to be a [perfect] pointer...but

it may say 'somewhere over in that direction,' " says auditory neuroscientist John Brugge of the University of Wisconsin. "It may take a number of neurons, all saying that, to actually accurately point in that direction."

Although he doesn't think his finding settles once and for all the issue of how sound location is coded, Middlebrooks says it would be logical for the auditory sense to record information chronologically while the visual system does so spatially. Information enters the visual system in map form, as an image projected on the retina; the brain merely preserves

the map as it passes the information along. "But in the auditory system, the ears are mapping frequency, [not location], and you have got to somehow take that information...and compute sound location," says Middlebrooks. Once the brain has made that computation, there is no a priori reason why it must store the information in the form of a map.

Despite that reasoning, the jury is still out on whether the Middlebrooks group has indeed found the auditory system's substitute for a spatial map. "The temporal pattern of firing of neurons changes as a function of sound location, so these patterns may constitute codes for sound location," concedes Caltech's Konishi. But, he adds, existence of the information is not enough. To settle the question, researchers must establish that the animal uses it. And that will require finding neurons that respond to the patterns, or experimental ways of altering the firing pattern to observe changes in the animal's response to sound. Those experiments are difficult, but without them the research community is left with the existential question of whether, when the auditory neurons tap out their neuronal Morse code, anyone is listening.

—Marcia Barinaga