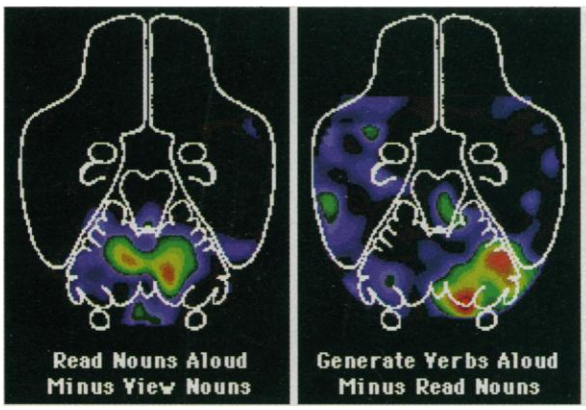
NEUROSCIENCE

The Cerebellum: Movement Coordinator or Much More?

For more than a century neurologists have observed that people with lesions in the cerebellum—a large brain structure nestled under the cerebral cortex at the back of the brain—walk erratically and fail at simple movement tasks like touching a finger to the tip of the nose. It seemed clear that the cerebellum's function is to help the brain coordinate movements, and much work in both animals and humans has supported that idea. But over the past decade, a growing clan of researchers has challenged that dogma. Far from being just a specialized control box for movement, they argue, the cerebellum participates in many brain functions, including the most exalted: cognition.

The work pointing in that direction includes neuroanatomical studies revealing extensive connections between the cerebellum and higher brain structures, tests showing that patients with cerebellar lesions do poorly on certain nonmotor tasks, and neuro-imaging studies of normal human subjects performing nonmotor tasks, such as those described on page 545 by Peter Fox of the University of Texas Health Science Center in San Antonio, James Bower of the California Institute of Technology, and their co-workers. Taken together, the results suggest that the cerebellum participates in functions ranging from the analysis of sensory information, to telling time, to solving puzzles. "Those who believe that the cerebellum is purely motor are going to have to take a hard look at that," says Harvard University neurologist and cerebellum researcher Jeremy Schmahmann, "because it seems not to be the case."

Not everyone agrees with that view. "From the basis of what I have seen, I wouldn't say that the cerebellum has changed from its main role as a motor-coordinating system," says neuroscientist Rodolfo Llinas of New York University Medical Center. Llinas belongs to a group of cerebellum researchers who believe the cerebellum's involvement in other brain functions can be explained as an offshoot of its motor-control function. The challengers of that traditional view present anything but a unified front: Their interpretations of their findings lead to a host of nonoverlapping models. "There is no final answer yet," says Schmahmann. "We are still very much in the working stages of this." But the ongoing ferment could eventually bring a new view of the cerebellum to the textbooks.



Thought process. Verb generation *(right)* produces distinctly different cerebellar activity than just reading a noun *(left)*.

For now, though, each new finding linking the cerebellum to yet another brain function just intensifies the theoretical conflicts. Take its role in cognition. An early clue to that role came 7 years ago from brain imaging studies by Steve Petersen, Marcus Raichle, and their colleagues at Washington University in St. Louis. They showed that the cerebellum is activated during cognitive tasks such as the verb-generation task, in which a person is shown a noun and asked to come up with a verb related to the noun, for example, "eat" when shown the word "apple." In contrast, if the subject was asked simply to repeat the noun, which involves similar speaking movements, the cerebellum was less active.

Since then other studies have also pointed to cerebellar involvement in cognitive tasks. Peter Strick's group at the Veteran's Administration Medical Center in Syracuse, New York, reported in 1994 that the cerebellum sends signals to some brain areas involved in cognition but not movement, and they also showed that solving a pegboard puzzle caused much more cerebellar activation than did the control task of simply moving the pegs in the board. And Julie Fiez, of Petersen's team, as well as others, has shown that patients with cerebellar damage, although they may seem cognitively normal, do poorly on verb-generation and puzzle-solving tests.

But these studies say nothing about what the cerebellum's actual role in cognition might be, says neuroscientist Richard Ivry of the University of California, Berkeley. "What exactly is the cerebellum doing?" Ivry asks. "Just to say it is involved in cognition doesn't get us any further down the road." Ivry's own experiments have led him to propose yet another, more specific, potential function for the cerebellum: His data suggest it acts as a clock that assists not only in the timing of motor control of fine movements, but also in other brain activities such as sensory discrimination.

Ivry's work builds on an observation from early this century that people with damaged cerebellums have trouble tapping out a rhythm with their fingers. That result was viewed as supporting the idea that the cerebellum is exclusively concerned with motor control. But Ivry decided to see whether the cerebellum was necessary for other forms of mental timing not involving movements.

When he asked normal individuals and people with cerebellar lesions to compare the time intervals between pairs of tones, he found that people with lesions did much worse than the controls did on this task, although they did as well as the normal subjects at judging the loudness of sounds. That, says Ivry, suggests that, while the cerebellum's main role may be motor control, the brain can "exploit the unique computational ability" of the cerebellum when it needs precise timing information for nonmotor functions.

Other neuroscientists, however, reject these new views of the cerebellum and argue that its apparent roles in cognition and timing could be explained by a well-established motor-related function of the cerebellum: It is active when someone is planning—or even thinking about—movements, such as when a tennis player imagines that she is playing a game. "How do you estimate time?" asks Washington University neurologist Tom Thach. "One way is you use movements," such as tapping a foot or counting out seconds. Even thinking to yourself, "one-thousand-one, one-thousand-two," would use the cerebellum's motor-planning functions, he says. And Ivry himself, when critiquing the cognitive findings by Petersen's group and others at the Society for Neuroscience meeting last November, noted that their experiments can't rule out the possibility that the cerebellum's role in the cognitive tasks is simply to prepare for the possible moves—such as the mouth movements needed to speak a word—necessary to execute the task.

He came to that hypothesis independently from his timing work, when he did a meta-analysis of 40 imaging studies involving cerebellar activation. He found that the cerebellum was consistently more active on the more "difficult" tasks—those in which there were a greater number of possible responses. For example, in the verb-generation test, the control task has only one possible response, reading the noun aloud. But when the study subjects have to find a verb, they have to consider many possible responses. It could be that the cerebral cortex is doing the cognitive work, generating all the possible responses, he suggests, and the cerebellum "is just faithfully going about preparing the motor programs to allow you to articulate all these different words."

Fiez maintains, however, that the evidence points to a more cognitive role for the cerebellum than simply plotting movements in the verb-generation test. For example, the way her cerebellar-lesion patient failed that test suggests a more cognitive problem: The words he chose often weren't even verbs. If Ivry's suggestion were correct "you might see a slowness" on the test, she says. "But it shouldn't affect your subject's ability to come up with the correct response."

Moreover, says Fiez, such arguments blur the line between motor and cognitive functions. If a process involves thinking about movement, should it be classified as cognitive or motor? Mentally choosing a word, or timing the space between tones, is something very different mentally, she argues, from the straightforward coordination and planning of actual movements.

Into this debate about motor and nonmotor functions comes the Bower and Fox team with evidence for yet another view of the cerebellum. They began the work a few years ago to test whether the cerebellum is involved in coordinating the acquisition of sensory information necessary for the brain to accomplish a variety of tasks, an idea Bower had gotten from studying the neuronal connections reaching the cerebellum from the tactile sensory areas of the rat brain.

The team made functional magnetic resonance images (fMRI) of the cerebellum while the subjects performed either of two pairs of tasks. In one pair, sandpaper was lightly rubbed across the fingers of both hands of the subject, who remained perfectly still. The subject was then asked to do nothing, or alternatively, to think about which sandpaper was rougher. In the other task, the subjects picked up little balls from cloth sacks attached to each hand, manipulated the balls in the fingers of both hands, and dropped them. In the second part of that task they were asked, before dropping the balls, do decide whether the balls were the same shape.

Consistent with Bower's hypothesis, the cerebellum was busiest when the subjects were discriminating between the sandpapers or balls. "The sensory stimulus is the same in [each pair of tasks]," says Bower. "What changes is how you are using the data." Moreover, of the four different tasks, the one that caused minimal activation was the one in which the subjects picked up, handled, and dropped the balls, suggesting that the cerebellum is more involved in sensory acquisition than in movement per se.

But proponents of the "motor-only" theory of the cerebellum are unconvinced. "Everyone has known about the sensory input coming into the cerebellum," says Thach. The Bower and Fox findings are perfectly consistent, he says, with the view that the cerebellum uses sensory information to guide movements.

Fox concedes that tactile sensation is necessary to guide movements, and that could be why the cerebellum is paying attention to it. But he says the team is already amassing data using sensory modalities such as hearing that are less obviously necessary for movement. "We will try to push this into purer and purer domains," Fox says, "to see if the utility to the motor system is a necessary criterion or not."

SOME POSSIBLE ROLES FOR THE CEREBELLUM

Proposed Function	Evidence in Humans With Cerebellar Damage
Motor coordination	Poorly coordinated movements
Cognitive function	Failure on specific cognitive tasks
Timing	Failure at tapping rhythms and judging timing of tones
General preparedness	Slow attention shift in response to cues
Sensory discrimination	No studies yet

Bower expects that it will not be a necessary criterion. Instead, he says, "I think that the cerebellum is coordinating the acquisition of sensory data on which the rest of the nervous system depends." He predicts that the cerebellum is called into action particularly in anticipation of difficult tasks in which there is a need for high-quality sensory information. That idea fits with Ivry's meta-analysis finding that the cerebellum is activated on more difficult tasks, and also with work by Eric Courchesne, at the University of California, San Diego, which suggests that the cerebellum helps prepare the brain for anticipated events.

Courchesne traces the roots of this notion back to some early signs of nonmovement functions for the cerebellum—observations made by several labs in the late 1970s and early 1980s that stimulating a rat's cerebellum with an electrode tens of milliseconds before presenting the animal with a visual or other sensory stimulus changed the way the animal's brain responded to the stimulus. For example, after cerebellar stimulation, the rat's brain gave a much bigger response to a flash of light against a light-colored background, much as if the cerebellum had somehow turned up the signal-to-noise ratio. There was no movement component to the tests, leading Courchesne to think the cerebellum might be helping the brain to focus its attention on sensory stimuli. "When you change your attention from one source of information to another," he says, "you are changing it with the anticipation that the new source of information is going to carry something that is important, that you have to prepare for."

To test this notion, he gave human subjects a test in which they had to shift their attention back and forth between sounds and visual images at a command. Normal subjects would miss information presented within less than a few hundred milliseconds of the signal to switch, but could catch information with almost total accuracy within half a second. People with cerebellar damage were about fivefold slower. "They were able to shift attention," says Courchesne, "but it took them many times longer." In work he presented at last month's meeting of the Cognitive Neuroscience Society in San Francisco, he and colleague Greg Allen showed with fMRI that, when normal subjects underwent a visual selective-attention task, their cerebellums were activated. "In this attention task, subjects make no motor response," Courchesne points out.

Courchesne takes his interpretation beyond sensory discrimination, suggesting that the cerebellum helps prepare a variety of brain systems to operate at full efficiency. People with cerebellar damage do not seem badly impaired, he says, because "each sensory and cognitive system can still do its thing." But deficiencies show up on specialized tests because without the extra assist from the cerebellum, "each [system] operates less efficiently, and the more a system is pushed, the more inaccuracies occur."

Whether Courchesne's or any other theory of the cerebellum can account for all the cerebellar data is unclear. "It may be premature at this point to try to come up with a global interpretation," says cerebellum researcher Enrico Mugnaini, of Northwestern University. "We need much more data." And it may be that the final answer is not "a 'this-or-that' situation," says Strick. "It could be all of the above."

–Marcia Barinaga

Additional Reading

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W. T. Thach, H. P. Goodkin, J. G. Keating, "The Cerebellum and the Adaptive Coordination of Movement," *Annual Reviews of Neuroscience* **15**, 403 (1992).

S.-G. Kim, K. Ugurbil, P. L. Strick, "Activation of a Cerebellar Output Nucleus During Cognitive Processing," *Science* **265**, 949 (1994).

E. Courchesne *et al.*, "Impairment in Shifting Attention in Autistic and Cerebellar Patients," *Behavioral Neuroscience* **108**, 848 (1994).