dicted. Instead of rapid acceleration, followed by a slowdown and subsequent speeding up, Gomi and Kawato found that the arm moved more smoothly, gradually accelerating and then decelerating as it came close to the final position. And the stiffness was not maintained, but decreased in the middle of the movement after an initial increase. "The brain does not send a signal that is a reproduction of the actual trajectory," Gottlieb notes.

Indeed, Gomi and Kawato think their results put the brain in full control of a movement. They propose that it works backward from visual information about the location of the target to figure out the final angle joints and muscle lengths in the arm once it reaches it target. Then it determines the timing and types of commands it needs to send those muscles to achieve those angles and lengths. "We believe that the brain possesses and utilizes an internal model of the arm for determining the motor command," Kawato says. Gottlieb agrees: "The brain knows enough physics to tell [the muscles] what to do; it doesn't rely on reflexes."

Lackner came to similar conclusions using a very different experimental apparatus, a round rotating room. Subjects placed in the center of this room lose the ability to tell whether or not it's spinning, and so can't rely on sensory clues to correct their movements for external forces, Lackner says. If the equilibrium point hypothesis is valid, subjects should be able to touch a target whether or not the room is spinning, because their movements should follow a set trajectory without undergoing corrections along the way. But that's not what Lackner found. When subjects first tried this task while rotating, they were way off. After several tries, however, their accuracy improved. Then, when the room stopped, the subjects missed the target again.

To Lackner, that "learning" indicates the brain gets a lot of feedback and makes adjustments in the course of a movement, something it shouldn't be able to do if it is simply launching the arm toward an endpoint. "There's a very detailed, ongoing monitoring [by the brain] in anticipation of ongoing movements," Lackner concludes. "We've demolished the hypothesis."

Not everyone agrees. MIT's Bizzi thinks the body may sense the room's rotation, even without conscious perception of it, and thus some unrecognized compensation may account for Lackner's results. And he and Tamar Flash of the Weizmann Institute in Rehovot, Israel, whose own work supports the equilibrium point hypothesis, argue that the Japanese workers used too simple a method for estimating the trajectory the arm should take, making their comparisons meaningless.

The situation is further complicated, however, by a split between Bizzi and others within the pro–equilibrium point hypothesis camp. Anatol Feldman, a Russian-born physicist turned neuroscientist who now works at the University of Montreal, first proposed the equilibrium point hypothesis in 1965. He doesn't think the brain picks an endpoint or has preset trajectories as Bizzi suggested. "It's a dynamic process that does not require a specific program [of action]," Feldman explains. Still, he concedes that even if the brain relies on the springlike properties of the musculoskeletal system to simplify motor control, it might nonetheless have some kind of internal model, albeit not like the one Kawato suggests.

Kawato, too, acknowledges the complexities of how the brain controls movements. "It's not so easy to do these experiments, and it's not so easy to analyze or interpret these data," he says. "They are good starting points for discussion, but I think the dispute will continue."

–Elizabeth Pennisi

EARTH SCIENCE

Impact Craters All in a Row?

After Jupiter got machine-gunned by the pieces of a shattered comet two summers ago, geologists naturally wondered whether the same thing had ever happened to Earth. At last month's Lunar and Planetary Science Conference in Houston, planetary geologist Adriana Ocampo of the Jet Propulsion Laboratory in Pasadena, California, and geologist Kevin Pope of Geo Eco Arc Research in La Cañada, California, announced they had found what look like the scars of a similar rapid-fire impact: a string of three 12-kilometer impact craters in the Sahara of northern Chad.

If Pope and Ocampo are right—and for now they face plenty of skepticism—geologists would have more evidence of the cosmic hazards menacing Earth. They would also have another indication that the Late Devonian period, a time of mass extinctions roughly 365 million years ago, was a particularly hazardous time. Geologists had already identified debris around the world from several impacts in the Late Devonian. And that's also when Ocampo and Pope think the debris of a dismembered 1- to 3-kilometer object slammed into the Chad site.

Neither Ocampo nor Pope has ever set foot in Chad, however. Geologists on the ground had already confirmed that an impact created one crater, but Ocampo and Pope are inferring the same origin for its two fainter companions based only on 1994 radar images from the Space Shuttle. That was not enough to convince cratering specialists at the meeting. In the absence of rock samples, says John McHone of Arizona State University, "I'm just not happy with the Chad site being a chain." Adds cratering specialist Richard Grieve of the Geological Survey of Canada, "There's no geological evidence that they're craters" rather than eroded traces of buried volcanoes.

Clinching evidence is available only for the 12.6-kilometer Aorounga, at one end of the chain. In 1992, a French group including Jean-François Becq-Giraudon of the French Geological Survey and Bureau of Mines in Orléans, France, visited the site and established that the flat-lying rock beds around the feature had indeed been turned upward by a great blast. They also collected quartz grains scarred by the shock of an impact.

Until they can match that kind of evidence, says Pope, "we do want to be careful not to say these are confirmed as two more impact craters." But he thinks that the circumstantial evidence is strong. "It's not only that they are circular features; they also exhibit a pattern similar to Aorounga's—circular depressions with a central peaklike structure." And he sees no signs of volcanic activity.

If he and Ocampo are right, the Late Devonian was a dangerous time indeed. Microscopic spherules of glass scattered across Belgium and China point to two sizable impacts

JPL/NASA

Convincing likeness? Faint companions to the impact crater visible at left in this Shuttle radar image may record a string of impacts.

1.5 million years apart (*Science*, 8 January 1993, p. 175). And in January's *GSA Today*, geologist John Warme of the Colorado School of Mines and paleontologist Charles Sandberg proposed that still another impact triggered a huge underwater landslide in Nevada about 3 million years earlier.

The spherules had already provoked speculations that a shower of comets, dislodged from the comet cloud surrounding the solar system by a passing star, pelted Earth and triggered the Late Devonian mass extinction, when 70% of all invertebrate species in the oceans died out. But for the Aorounga chain to be confirmed as part of an impact shower, someone will have to mount an expedition to northern Chad, where both the climate and the politics are unwelcoming. Watching the show on Jupiter, it seems, was easier than understanding the home planet.

–Richard A. Kerr