Solving the Brain's Energy Crisis

To understand brain evolution, anthropologists and neuroscientists are analyzing the energetic constraints on brain size—and how humans may have evolved a way around them

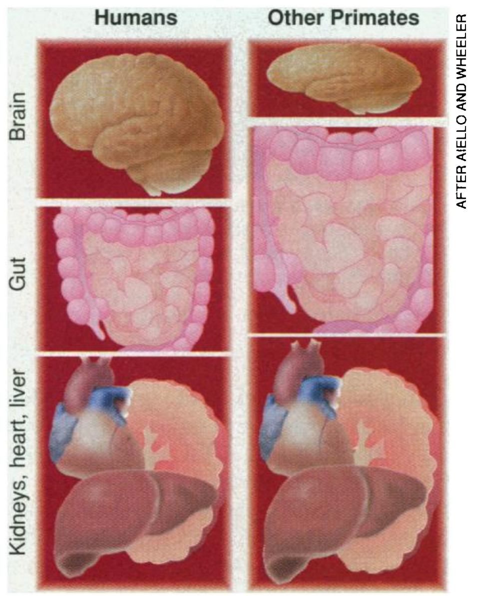
Humans have voracious brains. A newborn's brain consumes 60% of the energy the baby takes in. And that's just the beginning. That lump of gray matter doubles in size in the first year of life, and by adulthood, human brains weigh roughly a kilogram more than the brains of similar-sized mammals. Many researchers think energy intake limits brain size in many mammals. Yet the human brain and body as a whole don't use any more energy than smaller brained mammals of similar body size, so something must be making up for the brain's outsized appetite. As Leslie C. Aiello, a paleoanthropologist at University College London, puts it: "Where does the energy come from to fuel the large brain?" And if there is an energetic constraint on how big a brain can get, how did our ancestors overcome that limit?

Last month at the annual meeting of the American Association of Physical Anthropologists (AAPA), anthropologists debated two solutions to the brain's energy crisis: One, called the expensive tissue hypothesis, is that big brains in adults are fueled by the energy saved in humans' relatively small gastrointestinal (G.I.) tracts, which we can afford because of our high-quality diet. The other idea, the maternal investment hypothesis, proposes that most of the extra energy comes early in life—from mom, through the placenta during pregnancy and through breast milk between birth and age 4, when the human brain reaches 85% of its adult size.

At the moment, as researchers test and amplify each theory, it's unclear if either one is right; it may be that both play a role at different times in development. Either way, a growing number of anthropologists and neuroscientists are analyzing the potential constraints on brain evolution, testing their ideas with data from genetics, neuroscience, and comparative physiology. "The notion of understanding brain change in terms of the constraints on the body is an interesting and novel way of coming at this problem," says Cornell University neuroscientist Barbara Finlay.

Most evolutionary theories focus on the environmental or social factors that might have favored big brains, but this approach analyzes another variable: the underlying physical constraints that had to be overcome to build an oversized brain. By putting the two together, researchers hope to come up with more realistic evolutionary scenarios of how changes in our ancestors' behavior or ecology, such as hunting and living in large groups, helped them evolve bigger brains. Says paleoanthropologist Dean Falk of the State University of New York, Albany: "I'm really all for this approach. We have to attend to the energetics or we're not going to get selection for a bigger brain going on at all."

Researchers have long known that an animal's body size is a critical influence on brain size, as shown at the turn of the century by renowned Dutch paleontologist Eugene Dubois. Brains consume large quantities of energy in making neurotransmitters and firing axons, and bigger bodies have bigger hearts and lungs to supply more energy and oxygen to the brain. That's why elephants and baleen whales can have brains four to six times larger than those of humans. But humans are different. Our brains have tripled in size since Lucy and her fellow australopithecines, with brains roughly the size of a chimpanzee, began to walk upright on the African savanna 3 million years ago. But our bodies aren't even twice as big. "Humans, in fact, have the largest brain size relative to body size among placental mammals," says University of Zurich primatologist Robert D. Martin.



Gut-wrenching trade-off. Compared to other primates, humans have small guts, spending their energy on big brains instead.

Nor do humans conform to another pattern that Martin noticed in the early 1980s when he was pondering the question of human brain size. Research on basal metabolic rates, or how much energy an animal consumes while resting, showed that in mammals, the size of the newborn's brain tends to correlate with the mother's metabolic rate. Martin and others reasoned that supporting a bigger brain requires a higher energy consumption. Yet humans' basal metabolic rate is no higher than that of large sheep, which have brains five times smaller. Humans are apparently getting enough energy to feed their brains without increasing their overall energy intake, so it must be coming from some other source.

That source is the gut, according to the expensive tissue hypothesis, first proposed in 1995 by Aiello and physiologist Peter Wheeler of Liverpool John Moores University and revised last month by Aiello at the AAPA. The pair reviewed studies of humans and found that most of the basal metabolic rate—more than 70%—goes to fuel the brain, heart, kidney, liver, and G.I. tract. To find out if the demands of any of these organs were reduced to fuel the human brain, they compared the mass of each organ in adult humans with that expected for a primate of similar body size. Only the G.I. tract was smaller than expected—and it was about 60% of the size expected for a similar-sized primate. "The increase in mass and energy consumption of the human brain appears to be balanced by an almost identical reduction in the size of the gastrointestinal tract," concludes Aiello.

Aiello speculates that we could reduce our gut size to free up energy for a larger brain because of a dietary change that was taking place as brain size expanded. Our ancestors were shifting from a heavily vegetarian diet, which requires a massive gut to digest plants and nuts, to a more easily digestible, nutritious diet that included meat and requires less gut tissue.

Other researchers are now testing Aiello's idea. Harvard University primatologist Richard Wrangham and his students compared pigs—animals "rumored to be quite smart," says Wrangham—with mammals such as cattle, sheep, goats, and deer. Pigs have small stomachs compared with these mammals, but their brains are no larger, showing that the gut-brain trade-off didn't apply to them. Other studies have shown that the theory doesn't hold for birds or bats. In fact, it may apply only to some primates. But Aiello and Wrangham aren't bothered by this. "Other animals, such as birds, have different energetic challenges," says Aiello. Birds, for example, put their energy into large hearts for flight and have

In Mice, Mom's Genes Favor Brains Over Brawn

University of Zurich primatologist Robert D. Martin remembers the shock he got when behavioral neuroscientist Eric B. Keverne invited him to take a look inside the refrigerator in his lab at the University of Cambridge. He saw bodies of chimeric mice—some with big brains and small bodies, others with small brains and big bodies.

What surprised Martin was that the big-brained mice were bred to express more copies of genes inherited from their mothers, while those with the big bodies expressed more paternal genes. That result parallels Martin's notion that in humans, mothers invest extra energy in their young to promote larger brains (see main text).

Keverne's genetic studies in mice suggest a possible mechanism through which mothers might promote such an expansion of the brain. He studies a process called genomic imprinting, in which regulatory genes silence one copy of a gene—either the one from the father or the one from the mother—so that offspring get just a single dose of the gene. The mice in his freezer, research published 2 years ago in the *Proceedings of the Royal Society, London*, suggest that "the selection pressures for a big brain are coming through the matriline," says Keverne.

It may seem odd that mothers and fathers select for different features in their offspring, but evolutionary biologists say that males and females often have different strategies for propagating their genes—mating strategies being the prime example. In the mice, the maternal genes were expressed in the neocortex and portions of the "executive brain" important for reasoning, while the paternal genes were expressed in the brainstem, which controls more instinctive and hormonally driven behavior such as sex. Martin argues that although it costs more to invest in brainy young, for mothers this "is the best long-term investment. ... Mothers are pushing for the highest quality [offspring] they can afford."


E. B. KEVERNE / UNIVERSITY OF CAMBRIDGE

Brains vs. brawn. Mice bred to overexpress maternal genes have big brains *(top)*, while those expressing more paternal genes have big bodies *(above)*.

But when it comes to fathers, the researchers are left speculating; no one knows why fathers would favor big bodies over big brains. One possibility, Martin suggests, is that fathers' genes may survive best when there are many offspring. Thus fathers' genes may be selected to promote less expensive offspring with small brains—which allows mothers to have more offspring.

Primates, with their complex social structures, have a proportionally large executive brain, and this trend is most pronounced in humans. Thus Keverne speculates that genomic imprinting may have been a factor in human brain evolution, too. Studies of human genetic diseases do show that maternal and paternal genes make different contributions to brain development—but the nature of each contribution has yet to be parsed. –A.G.

---

small guts and brains. "I'm not worried about it," agrees Wrangham. "I think Aiello and Wheeler have got the right answer."

But Martin thinks another source of energy may be more important in building and fueling big brains: energy donated by the mother. He thinks the obvious place to look for extra energy in humans is during the "crunch time" for brain development—from gestation until age 4, when the brain reaches 85% of its full adult size. That trail led straight to the mother, who "provides most of the energy in gestation, then in lactation, which is 3 to 4 years in hunter-gatherers," says Martin.

Indeed, work by other researchers makes it clear that during gestation at least, the human system has evolved to allow maximum energy transfer between mother and offspring. The human placenta is particularly greedy, sucking nutrients from the mother's bloodstream more aggressively than in other primates, according to recent work by Harvard University evolutionary biologist David Haig. He notes that in humans the placenta invades the uterine lining more deeply than in other primates. This energy drain continues in lactation. Human gestation is over well before brain growth is complete, in contrast to other animals. Lactation takes up the slack, says Martin. In effect, human gestation continues in the first year of life. "We achieve our big brains in continuing our fetal pattern of growth in the first year of life, and human milk must be pumping in energy," says Martin. Thus humans can afford such big brains because their mothers make such an enormous investment in them, nursing them until brain growth is almost complete.

The only way human mothers can donate so much energy to brain growth in their infants is by taking in extra energy themselves. Paleoanthropologist Alan Walker of Pennsylvania State University, University Park, has an as-yet-unpublished proposal about how human ancestors met this need. Like Aiello, he thinks the switch to a diet high in protein and fat 2 million years ago, with the advent of hunting, was crucial. In his scenario, however, the new diet's role in brain evolution allowed a fetus to pull this much energy from the mother without killing her.

Social changes may have played a role, too. As our species evolved, mothers could increasingly count on family members to feed them and to help care for their young, so they could invest more in pregnancies and infants, says Cambridge University behavioral neuroscientist Eric Keverne. "Mothers were getting access to more and more energy, through tool use, cooking, eating meat," says Martin. "It's progressive." So in a positive feedback loop, a higher energy intake allowed larger brains—which in turn led to even more energy intake.

So where do humans muster the energy to fuel their brainpower—mom or cheap guts? Aiello suggests both may be true. Humans may tap mom's energy resources during the period of peak brain growth in gestation and early childhood. Once weaned, small guts in later childhood and adulthood would free up energy to help sustain the expensive brain.

Despite the enthusiasm for this approach, other researchers have offered a basic challenge to the assumption behind both ideas. Although huge quantities of energy go into a working brain, energy may not be the key limiting factor in brain size, says Oxford University evolutionary biologist Paul Harvey: "There's no reason to suspect that the reason other mammals don't have big brains is that they are energetically limited."

He challenges the data that led to the assumption of an energy limit on brain growth: the link between metabolism and brain size. He and Oxford colleague Mark Pagel showed in 1988 in the journal *Evolution* that animals with high basal metabolic rates for their body size, such as shrews, do not produce large-brained young. "I don't see this as an energetics problem," says Harvey, whose work with Pagel suggests that the way to grow larger brains is to have long gestation times, late weaning, and fewer offspring per litter.

Others aren't ready to give up on the correlation. Martin, responding in a talk at the AAPA, says that if one incorporates length of gestation and lactation and animals' degree of independence at birth, the link between metabolism and brain size holds up.

Despite the critics, the energetic approach is making its mark, as researchers accept the possibility of energetic constraints on evolution. This "is making us do experiments to measure how much energy the mother is putting into her offspring," says Francisco Aboitiz, a neuroscientist at the University of Chile in Santiago; he is comparing brain growth in different species of rats to see how different parts of the brain have evolved in response to varying ecological conditions. In the end, both hypotheses may be pieces in a complex puzzle—important physiological constraints that had to be overcome before selection could sculpt a larger brain. "I'm sure there's no single answer," says Aiello: "These things all work together. It all depends on your ecology." And perhaps on the size of your gut or the amount of your mother's energy.

–Ann Gibbons

ASTRONOMY

Taiwan, U.S. Team Up to Chase Shadows

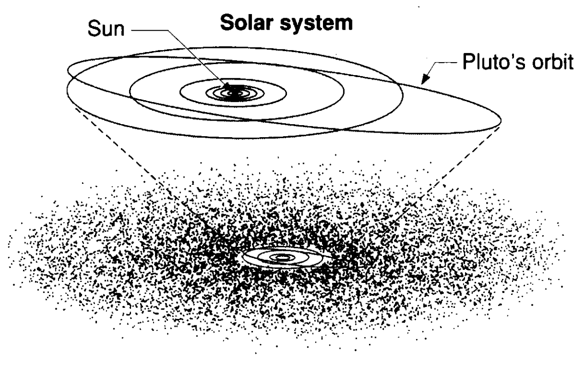
When a star in a telescope's view winks out, a passing cloud or bird is usually to blame. But astronomers think that sometimes, the shadow could be cast by a distant ball of ice and dust in a vast, uncharted comet reservoir beyond Neptune known as the Kuiper Belt. A U.S.-Taiwanese collaboration has set out to chase these shadows. It is building a robotic, three-telescope array to look for stellar blackouts from a mountain range in central Taiwan, beginning in 2000.

By counting and measuring these blackouts, the Taiwanese American Occultation Survey, or TAOS—a million-dollar joint effort of NASA, the Lawrence Livermore National Laboratory in California, Taiwan's Academia Sinica and National Central University, and others—aims to estimate the number of objects in the Kuiper Belt and determine their size distribution. The results could force astronomers to "rethink the comets," says astronomer David Jewitt of the University of Hawaii, Honolulu, co-discoverer of the first Kuiper Belt object in 1992.

Jewitt explains that comets, stored in the Kuiper Belt and the more distant Oort Cloud, "are thought to be fragments from the solar nebula that didn't change." The new size census could show how pristine they are, he says. "If they have been repeatedly smashed, it's likely they have changed," says Jewitt, who is enthusiastic about the new survey, although he is not a participant.

Objects from the Kuiper Belt can be seen when they plunge into the inner solar system as comets. All but the largest objects in the belt itself—those with diameters exceeding 100 kilometers—are invisible to ground-based telescopes, however. So Livermore astronomer Charles Alcock and his U.S. and Taiwanese colleagues conceived of the star-shadow strategy for counting the billion or so icy bodies there. Alcock explains that the technique should detect objects with diameters as small as 1 to 2 kilometers at the distance of the Kuiper Belt. If the object lies much farther away, starlight bleeding around it should wash out the shadow. If the shadow is due to a much closer object, a large telescope should be able to spot the culprit directly.

The comet hunters plan to monitor star fields that lie along the ecliptic, the plane of the solar system, and contain many bright, pinpoint stars. Three wide-angle, half-meter telescopes, linked electronically, will be dedicated to the task. Two will stand 10 meters apart—far enough that electronic noise and other sources of error are unlikely to affect both simultaneously. A third, "outrigger" scope will observe the same region of the sky from 7 to 10 kilometers away.



Uncharted cloud. The icy swarm of the Kuiper Belt is thought to extend far beyond the orbits of Neptune and Pluto.

SOURCE: A. COCHRAN/UNIV. OF TEXAS/NASA

When a star blinks out, other checks will kick in before the shadow will be tallied as a denizen of the Kuiper Belt. If many adjacent stars were also blotted out, for example, that would suggest that the culprit was a bird or plane. If the stellar eclipse registers at slightly different times at the outrigger and at the other telescopes—proportional to Earth's 30-kilometer-per-second velocity around the sun—observers at large telescopes will be asked within 2 hours of the sighting whether they can see the interloper. If they can, the odds are it's something too nearby to be in the belt. If not, the TAOS collaborators will estimate its size from how long the occultation lasts.

Because the swarms of objects in the Kuiper Belt are scattered through such a large volume of space, the telltale alignments should be rare. So the survey plans to take snapshots as rapidly as five times per second for some 3000 stars at a time, collecting an unprecedented billion starlight measurements nightly from all three telescopes. Even so, the researchers expect to identify just a handful of comet occultations—from three to 1000—in the 100 billion measurements to be taken per year.

To deal with the flood of data, the comet census will draw on data-crunching technology pioneered in another star survey directed by Alcock, called the MACHO project. MACHO also monitors vast swarms of stars, but it is searching for the temporary brightening or "microlensing" of a star that results when a distant, massive object—a planet or a burned-out star—passes across the line of sight, and its gravity focuses the light of the background star.

NASA is providing $350,000 to the Kuiper Belt project over 3 years, with an additional $220,000 this year coming from Livermore's internal coffers. Taiwan is footing an equal or larger share of the cost, team members say, and will pay for two of the three telescopes, which are now on order.

Locating the observatory in Taiwan makes sense because the ecliptic is high in the sky there. But Taiwanese participants also hope that the facility will help their country nurture its own world-class scientific establishment. "There is a widely held view in Taiwan that science and technology is the future of the country's well-being," says Kwok Yung "Fred" Lo, an Academia Sinica astrophysicist on the TAOS project. "TAOS is special because it is the first scientifically significant astronomy project to be located in Taiwan."

–Peter Weiss

Peter Weiss is a science writer in Washington, D.C.