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SANTIAGO RAMÓN Y CAJAL, THE SPANISH NOBEL-WINNING BIOLogist who mapped the neural anatomy of insects in the decades before World War I, likened the minute circuitry of their vision-processing neurons to an exquisite pocket watch. He likened that of mammals, by comparison, to a hollow-chested grandfather clock. Indeed, it is humbling to think that a honeybee, with its milligram-size brain, can perform tasks such as navigating mazes and landscapes on a par with mammals. A honeybee may be limited by having comparatively few neurons, but it surely seems to squeeze everything it can out of them.

At the other extreme, an elephant, with its five-million-fold larger brain, suffers the inefficiencies of a sprawling Mesopotamian empire. Signals take more than 100 times longer to travel between opposite sides of its brain—and also from its brain to its foot, forcing the beast to rely less on reflexes, to move more slowly, and to squander precious brain resources on planning each step.

We humans may not occupy the dimensional extremes of elephants or honeybees, but what few people realize is that the laws of physics place tough constraints on our mental faculties as well. Anthropologists have speculated about anatomic roadblocks to brain expansion—for instance, whether a larger brain could fit through the birth canal of a bipedal human. If we assume, though, that evolution can solve the birth canal problem, then we are led to the cusp of some even more profound questions.

One might think, for example, that evolutionary processes could increase the number of neurons in our brain or boost the rate at which those neurons exchange information and that such changes would make us smarter. But several recent trends of investigation, if taken together and followed to their logical conclusion, seem to suggest that such tweaks would soon run into physical limits. Ultimately those limits trace back to the very nature of neurons and the statistically noisy chemical exchanges by which they communicate. "Information, noise and energy are inextricably linked," says Simon Laughlin, a theoretical neuroscientist at the University of Cambridge. "That connection exists at the thermodynamic level."

Do the laws of thermodynamics, then, impose a limit on neuron-based intelligence, one that applies universally, whether in birds, primates, porpoises or praying mantises? This question apparently has never been asked in such broad terms, but the scientists interviewed for this article generally agree that it is a question worth contemplating. "It's a very interesting point," says Vijay Balasubramanian, a physicist who studies neural coding of information at the University of Pennsylvania. "I've never even seen this point discussed in science fiction."

Intelligence is of course a loaded word: it is hard to measure and even to define. Still, it seems fair to say that by most metrics, humans are the most intelligent animals on earth. But as our brain has evolved, has it approached a hard limit to its ability to process information? Could there be some physical limit to the evolution of neuron-based intelligence—and not just for humans but for all of life as we know it?

THAT HUNGRY TAPEWORM IN YOUR HEAD

THE MOST INTUITIVELY OBVIOUS WAY in which brains could get more powerful is by growing larger. And indeed, the possible connection between brain size and intelligence has fascinated scientists for more than 100 years. Biologists spent much of the late 19th century and the early 20th century exploring universal themes of life—mathematical laws related to body mass, and to brain mass in particular, that run across the animal kingdom. One advantage of size is that a larger brain can contain more neurons, which should enable it to grow in complexity as well. But it was clear even then that brain size alone did not determine intelligence: a cow carries a brain well over 100 times larger than a mouse's, but the cow isn't any smarter. Instead brains seem to expand with body size to carry out more trivial functions: bigger bodies might, for example, impose a larger workload of neural housekeeping chores unrelated to intelligence, such as monitoring more tactile nerves, processing signals from larger retinas and controlling more muscle fibers.

Eugene Dubois, the Dutch anatomist who discovered the skull of *Homo erectus* in Java in 1892, wanted a way to estimate the intelligence of animals based on the size of their fossil skulls, so he worked to define a precise mathematical relation between the brain size and body size of animals—under the assumption that animals with disproportionately large brains would also be smarter. Dubois and others amassed an ever growing database of brain and body weights; one classic treatise reported the body, organ and gland weights of 3,690 animals, from wood roaches to yellow-billed egrets to two-toed and three-toed sloths.

Dubois's successors found that mammals' brains expand more slowly than their bodies—to about the ¾ power of body mass. So a muskrat, with a body 16 times larger than a mouse's, has a brain about eight times as big. From that insight came the tool that Dubois had sought: the encephalization quotient, which compares a species' brain mass with what is predicted based on body mass. In other words, it indicates by what factor a species deviates from the ¾ power law. Humans have a quotient of 7.5 (our brain is 7.5 times larger than the law predicts); bottlenose dolphins sit at 5.3; monkeys hover as high as 4.8; and oxen—no surprise there—slink around at 0.5 [*see box at right*]. In short, intelligence may depend on the amount of neural reserve that is left over after the brain's menial chores, such as minding skin sensations, are accounted for. Or to boil it down even more: intelligence may depend on brain size in at least a superficial way.

As brains expanded in mammals and birds, they almost certainly benefited from economies of scale. For example, the greater number of neural pathways that any one signal between neurons can travel means that each signal implicitly carries more information, implying that the neurons in larger brains can get away with firing fewer times per second. Meanwhile, however, another, competing trend may have kicked in. "I think it is very likely that there is a law of diminishing returns" to increasing intelligence indefinitely by adding new brain cells, Balasubramanian says. Size carries burdens with it, the most obvious one being added energy consumption. In humans, the brain is already the hungriest part of our body: at 2 percent of our body weight, this greedy little tapeworm of an organ wolfs down 20 percent of the calories that we expend at rest. In newborns, it's an astounding 65 percent.

STAYING IN TOUCH

MUCH OF THE ENERGETIC BURDEN of brain size comes from the organ's communication networks: in the human cortex, communications account for 80 percent of energy consumption. But it appears that as size increases, neuronal connectivity also becomes more challenging for subtler, structural reasons. In fact, even as biologists kept collecting data on brain mass in the early to mid-20th century, they delved into a more daunting enterprise: to define the "design principles" of brains and how these principles are maintained across brains of different sizes.

A typical neuron has an elongated tail called the axon. At its end, the axon branches out, with the tips of the branches forming synapses, or contact points, with other cells. Axons, like telegraph

IN BRIEF

Human intelligence may be close to its evolutionary limit. Various lines of research suggest that most of the tweaks that could make us smarter would hit limits set by the laws of physics.

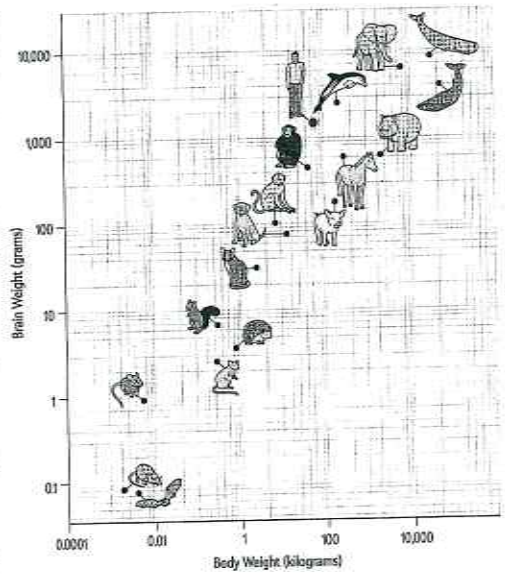
Brain size, for instance, helps up to a point but carries diminishing returns: brains become energy-hungry and slow. Better "wiring" across the brain also would consume energy and take up a disproportionate amount of space. **Making wires thinner** would hit thermodynamic limitations similar to those that affect transistors in computer chips: communication would get noisy.

Humans, however, might still achieve higher intelligence collectively. And technology, from writing to the Internet, enables us to expand our mind outside the confines of our body.

A SCALING LAW AND ITS EXCEPTIONS

Brain-Size Outliers

Whether they are smarter or not, larger animals typically have larger brains, although brain size grows not as a fixed percentage but as the ¾ power of body mass, a law that in the logarithmic scale below is represented by a straight line. Unusually smart animals, then, are those that deviate from this power law and place farther up than the line; humans beat the law by a factor of 7.5, the best of any species. Beyond a point, however, increasing brain size brings diminishing returns [*see box on page 26*].



SOURCE: "BRAIN SIZE IN VERTEBRATES," BY P.A.M. VAN DONGEN, IN THE CENTRAL NERVOUS SYSTEM OF VERTEBRATES, VOL. 3, EDITED BY R. NIEUWENHUYS ET AL. SPRINGER, 1998

Graphic by Bruno Bird Design