Number of the beasts

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More and more animals are revealing unsuspected mathematical talents. And they're teaching us a thing or two about how our own brains deal with numbers, says Emily Sohn MATHEMATICS often ranks alongside language and opposable thumbs as one of those things that separate man from beast. But again and again, the beasts are proving us wrong. "Every time people say animals can't do X," says Irene Pepperberg, who has spent years studying the skills of an African grey parrot named Alex, "we find yes, they can. They can do X + 1."

From birds that count, to chimpanzees that add, to salamanders that know the difference between two and three, it looks as though an inborn sense of number is one of the most basic cognitive abilities around. And a range of studies show that animals and people deal with numbers in some remarkably similar ways.

As cross-species findings continue to pour in, researchers think they are getting closer to understanding how brains work with numbers. Universal quirks in mathematical abilities could shape better teaching strategies, and decoding the number response might reveal some basic brain mechanisms. Understanding numeracy might even yield clues about what goes wrong in disorders such as schizophrenia and autism.

That numeracy skills are found throughout the animal world makes a lot of sense. Figuring out which tree has more berries on it, or determining whether there are more friends than enemies in an area, are matters of life and death. "If you know there are six lions in the pride and you only see four," says behavioural neuroscientist Randy Gallistel of Rutgers University in New Jersey, "there is probably some survival value to wondering where the other two are."

Not surprisingly, some animals are more gifted than others (see Graphic). "You go from the very simplest perceptual recognition of bigger versus smaller to the absolute be-all, end-all of being able to understand complicated mathematical equations," says Pepperberg, who works at the University of Arizona in Tucson and is also a visiting professor at the Massachusetts Institute of Technology.

Alex, a 27-year-old parrot in Pepperberg's lab, for example, can count and distinguish between more and less, among other skills. He can look at a collection of blue and red blocks and tell how many blue blocks there are. Pepperberg also believes that Alex is learning not only that the symbol "3" represents "threeness", but also that the symbol "4" represents something bigger. Chimpanzees can do similar tasks. Pigeons appear to be less numerate but can distinguish between different numbers of objects, however big the objects are or however much space they take up. Rats don't seem to grasp abstract concepts of number at all, but can learn to press a lever close to a specified number of times.

But whatever mathematical tricks animals can be taught, they learn about numbers in a different way to children, says Claudia Uller, a cognitive scientist at the University of Essex in Colchester, UK. For one thing, children learn much faster than primates. "In order to teach a chimpanzee to learn a symbolic number system, you have to make it learn 'oneness', then 'twoness', then 'threeness', and that takes it forever," Uller says. Children, on the other hand, usually reach some kind of "eureka" moment at around age 3, when it just clicks that there is always a bigger number than the one you've just counted. It is more interesting to look at what animals can do spontaneously, without any training at all, she says - that's what tells you about our innate sense of number.

One classic technique for testing innate number abilities was developed for studying human babies. More than a decade ago, Karen Wynn, a developmental psychologist now at Yale University, found that babies look measurably longer at things that are novel or surprising. For example, when 6-month-old babies see one doll go behind a screen, then another, they expect to see two dolls if the screen is lifted. The babies will look longer if they see three dolls, or one, rather than two. This may indicate a primitive ability to count. Similar experiments have shown that rhesus macaques can add and subtract small numbers of objects, as can cotton-top tamarins, an even more distant relative of ours.

More recent experiments have explored a still more basic number skill shared by primates and babies: the ability to understand "more" and "less". Last year Harvard psychologist Susan Carey and her colleagues showed that 10 and 12-month-old babies will crawl up to a container with two cookies rather than just one. Likewise, rhesus macaques will choose a box with three apples rather than two.

Hoping to look even further back in our evolutionary history, Uller did the same experiment with red-backed salamanders. Instead of cookies or fruit, salamanders chose between test tubes containing different numbers of fruit flies. Consistently, Uller found, the amphibians touched their snouts to the tube that held more flies. Her study was the first to show that an animal other than a primate might be able to pick the larger of two numbers of objects in the same way that babies do. "What this says," says Harvard biologist Marc Hauser, "is that the building blocks for higher mathematical capacity are built onto primitives that evolved way before we were even on the planet."

Similarities between different species are striking, Uller says, not only in what they can do, but in what they can't. Across the board, performance seems to drop off around the number four. "It's so incredible," she says. "If you give babies a choice between two and three, they'll go for three. At three versus four, they're random. At four versus six, they're random." Likewise, rhesus monkeys can understand one versus two and two versus three, but not three versus four or four versus six. Salamanders show the same patterns. Even human adults can keep track of four moving dots on a computer screen, but not more.

To some researchers, including Uller and Hauser, the universal failure at four suggests that the brain has two separate systems for dealing with numbers. One, called the large approximate system, covers the big numbers and relies on a keen sense of estimation. That would explain why rats and pigeons can learn to press a lever as many as 45 times to get a reward, but the margin of error increases as the target number gets bigger. Humans behave in the same way. You can test yourself: guess how many geese are in a flock, for instance, then count. You'll probably come pretty close.

The small number system, on the other hand, is theoretically more specific and precise. Also called "object indexing", this theory holds that the brain opens one "file" at a time to keep track of individual objects, but can have only four or five files open at once.

"To me, it raises more problems than it solves," says Gallistel, one of the most vocal critics of the two-system theory. Put simply, the problem is that you can add small numbers together to get a big one, or subtract one big number from another to get a small one, and these operations would require both systems. It is not clear how the system that handles the question could interact with the one that handles the answer.

Brian Butterworth, a neuropsychologist at University College London, sees further problems with the two-system explanation. He agrees we can look at a group of objects and estimate that there are lots of items, but thinks this is not the same as translating an estimate into a large number. Large number skills develop with language skills, he says.

But he also agrees that we are born with an ability to deal with small numbers. His explanation focuses on our uncanny ability to "subitise". Up to four or five objects, most people can tell how many there are just by looking, without counting each one. But if there are more objects, we have to count. Based on work with brain-damaged people who can't subitise, Butterworth argues that there is a "number module" in the brain: a cluster of cells that gives us an instinctive sense of small numbers. Either you have it or you don't (New Scientist, 3 July 1999, p 46).

He says that our brains have categories for "twoness", "threeness" and "fourness", just as they have categories for "greenness" or sharpness. For some reason, things change around five. Likewise, neuropsychologist Stanislas Dehaene, in his book The Number Sense, argues that a simple sense of number is as basic as a sense of colour. Both are useful ways for our brains to perceive the world. Advanced mathematics is more difficult, Dehaene says, because it relies on language and the ability to comprehend symbols.

All these theories scramble to explain some of the universal challenges that seem to come with large numbers. For example, it is much easier for both animals and people to distinguish between numbers when one is much bigger than the other. Thirty birds are obviously more than 15, for instance, while 15 and 14 birds can look the same at first glance. It is also easier to tell the difference between two and three things, for instance, rather than 49 and 50, even though the difference in each case is one.

The search to explain these basic effects has led to different theories about how the brain represents numbers. Does it have regions that know about discrete categories of "oneness" and "twoness", for example, as Butterworth and Dehaene suggest? How do we know about which order numbers appear in? And how do we manipulate numbers? One idea is that the brain creates some sort of map of different numbers. But there are two ways researchers think the map might appear. It could be that each number is given equal importance, and that they are spaced equally along a linear number line. As numbers get bigger, there are more to keep track of and so precision plummets. Another possibility is that the internal number line operates on a logarithmic scale: smaller numbers are dealt with more precisely and bigger numbers get more "compressed" in the brain, making it harder to tell them apart.

Results from behavioural experiments have failed to sort out which is the case, says Earl Miller, a cognitive scientist at the Picower Center for Learning and Memory at MIT. So he and colleague Andreas Nieder of the University of Tübingen in Germany went right to the source: individual cells in the brain.

Brain imaging studies had previously shown that an area called the prefrontal cortex becomes active when people think about numbers. And people with brain damage in that area lose their sense of number. So Miller and Nieder trained rhesus monkeys to judge whether consecutive images on a computer screen showed the same number of dots. Electrodes then recorded the activity of around 300 neurons in the prefrontal cortex as they carried out the task. Each image showed between one and five dots and to make sure the monkeys were using number to make their judgments, the dots had different sizes and positions.

The researchers found that different groups of neurons responded strongly to different numbers. Each individual neuron seemed to respond most strongly to one number. But they also showed exactly the property needed to form a number line, in that they "knew" something about the sequence of numbers before and after: a neuron's response would tail off as the number got bigger or smaller than its "favourite" number. So the responses of different groups of neurons overlapped. And when the researchers plotted exactly how much overlap there was, they found it was consistent with a logarithmic sequence.

Miller and Nieder are now working to pinpoint other brain areas and cells involved in recognising numbers. Already Nieder has unpublished data suggesting that a part of the brain called the posterior parietal cortex is the first area to respond when a monkey sees numbers. Next he wants to determine whether the same areas and cells respond when monkeys encounter numbers in other ways - by hearing different numbers of pulses, for example.

A detailed understanding of how the brain represents numbers could lead to more effective ways of teaching large numbers to children, Miller says. Seeing what works with animal training might suggest better ways to train kids in mathematical skills, for example.

He believes that understanding the general principles and mechanisms that the brain, particularly the prefrontal cortex, uses to categorise things by number, might eventually help us understand brain disorders where other forms of categorisation and conceptualisation go awry, such as schizophrenia, autism and attention deficit disorders. It's early days yet, he adds, but we might learn something about these very broad thought disorders by investigating how numeracy skills can go awry, and maybe even by testing how various brain chemicals affect how the brain learns and represents numbers in other animals.

For now, scientists are still trying to figure out just what animals can and can't do in order to delve deeper into our mathematical heritage. In a study published in Nature last April, for example, behavioural ecologist Bruce Lyon at the University of California, Santa Cruz, found that wild coots can count the eggs in their nests (vol 422, p 495). They then eject foreign eggs laid by other birds trying to offload their parenting responsibilities and add more of their own to compensate. "This was one of the very few studies showing counting in a wild animal as opposed to a laboratory setting," says Lyon. "So it connects counting back to the reason why they would be counting."

And Uller's next plan is to do her salamander study with shrimp and food pellets, to see if crustaceans will spontaneously go for more, just as babies, primates and salamanders do."I'm going down the line here," she says. "We are not in the insect domain yet. A colleague suggested we try roaches - two breadcrumbs on the left, three on the right." She laughs. "We're not there yet."

The power of one

The loner mathematician is a popular, if exaggerated, image. But new studies suggest that in nature, mathematical skills and social skills are indeed a rare combination.

"Orang-utans approach solving problems very, very differently from chimpanzees and humans or even salamanders," says Robert Shumaker from the Iowa Primate Learning Sanctuary in Des Moines. He thinks that social pressures might explain why different species have evolved subtle differences in their number skills.

One of the most telling examples involves self-restraint. Say you present an animal with two piles of hard-to-resist food, such as gumdrops. If the animal picks the lesser of two piles of gumdrops, it earns a larger reward. Going for this delayed gratification requires a huge amount of self-control. Orang-utans can do it. Chimpanzees can't.

Primatologist Sally Boysen of Ohio State University in Columbus has trained chimpanzees to do almost everything else imaginable involving numbers. But picking less food is something the animals just cannot do. "If, instead of candy, I put Arabic numerals down, they didn't have any problem pointing to the number "2" instead of the number "5" immediately," Boysen says. "They knew the rules but they could just not inhibit going for the actual things. It's as if the number symbol freed them from this biological dictate."

Chimpanzees are extremely social animals, constantly competing for resources. They may just be hard-wired to pick more when it comes to food, regardless of what the trainers says. Rhesus monkeys and capuchins have the same problem, Boysen says, as do salamanders and pigeons.

Orang-utans, on the other hand, can pick the smaller of two quantities without any problem at all, says Shumaker. Unlike chimps, orang-utans tend to spend lots of time alone. Without pressure to compete, Shumaker says, they may have better control over their minds and actions.

Emily Sohn Emily Sohn is a science writer based in Minneapolis.