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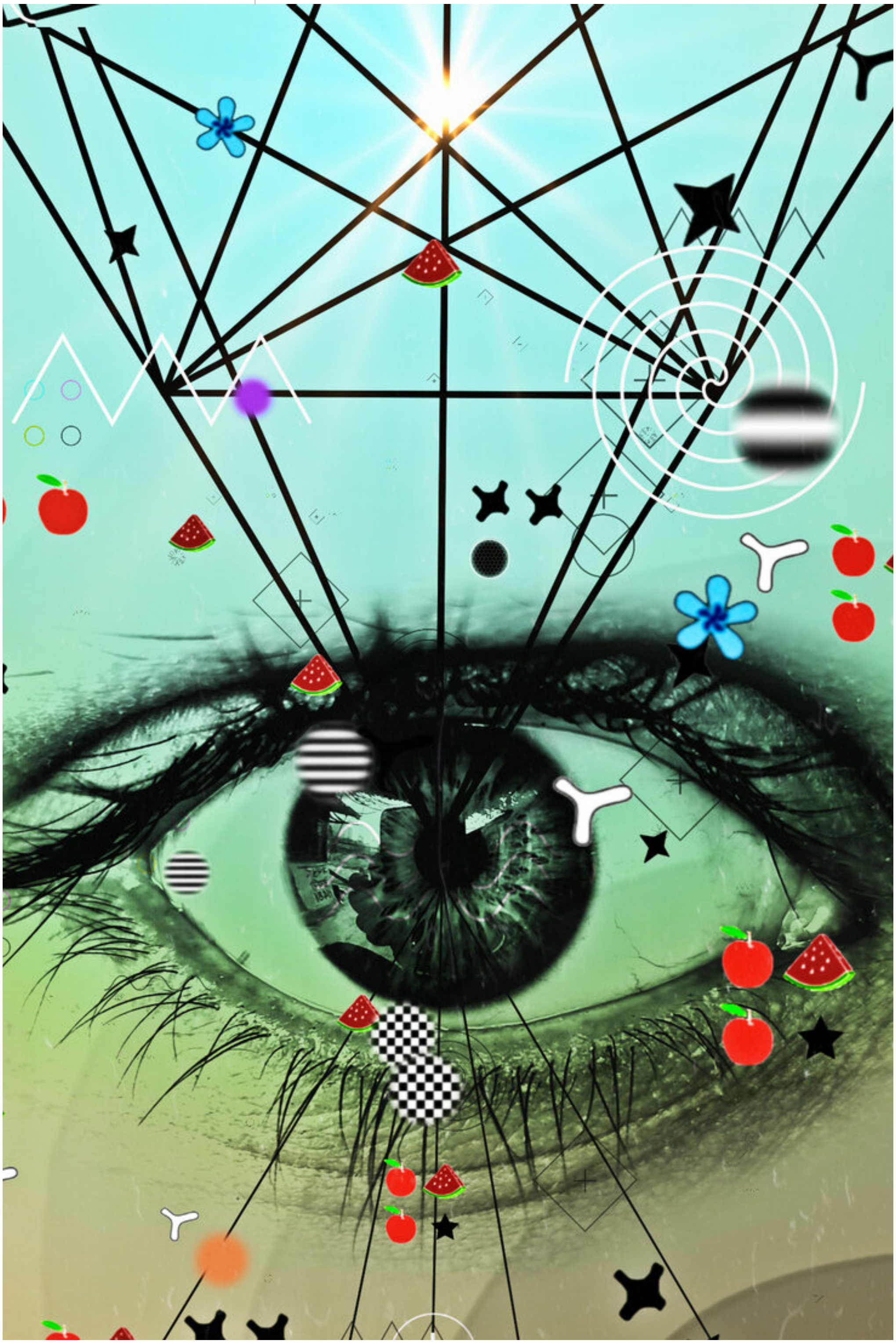


Is Geometry a Language That Only Humans Know?

Neuroscientists are exploring whether shapes like squares and rectangles — and our ability to recognize them — are part of what makes our species special.

By Siobhan Roberts

March 22, 2022

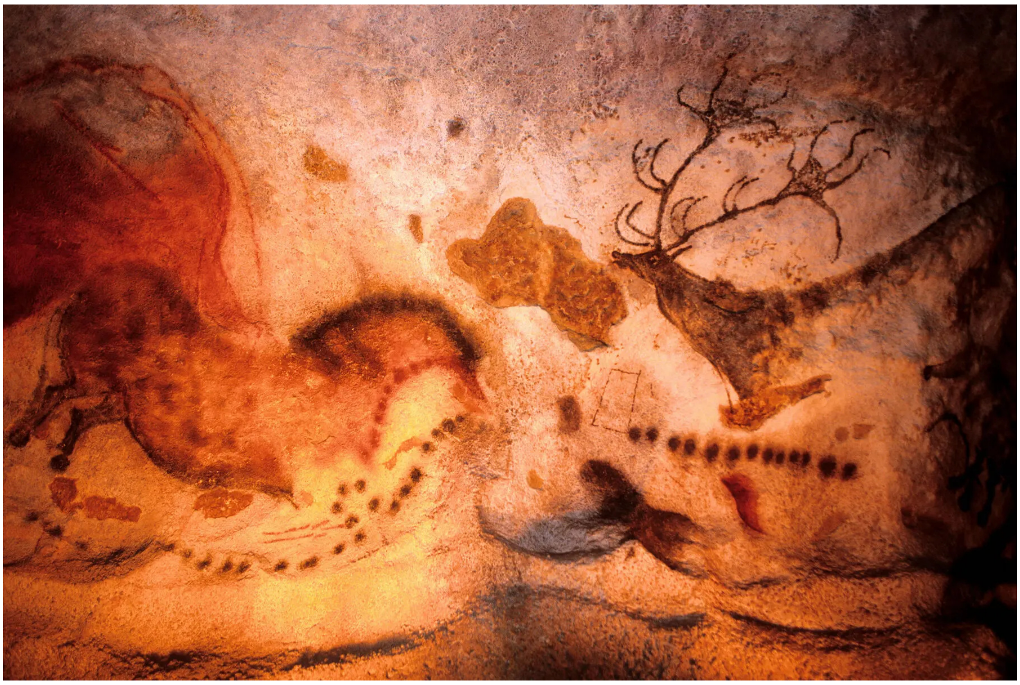
During a workshop last fall at the Vatican, Stanislas Dehaene, a cognitive neuroscientist with the Collège de France, gave a presentation chronicling his quest to understand what makes humans — for better or worse — so special.

Dr. Dehaene has spent decades probing the evolutionary roots of our mathematical instinct; this was the subject of his 1996 book, "The Number Sense: How the Mind Creates Mathematics." Lately, he has zeroed in on a related question: What sorts of thoughts, or computations, are unique to the human brain? Part of the answer, Dr. Dehaene believes, might be our seemingly innate intuitions about geometry.

Organized by the Pontifical Academy of Sciences, the Vatican workshop addressed the subject "Symbols, Myths and Religious Sense in Humans Since the First" — that is, since the first humans emerged a couple of million years back. Dr. Dehaene began his slide show with a collage of photographs showing symbols engraved in rock — scythes, axes, animals, gods, suns, stars, spirals, zigzags, parallel lines, dots. Some of the photos he took during a trip to the Valley of Marvels in southern France. These engravings are thought to date back to the Bronze Age, from roughly 3,300 B.C. to 1,200 B.C.; others were 70,000 and 540,000 years old. He also showed a photo of a "biface" stone implement — spherical at one end, triangular at the other — and he noted that humans sculpted similar tools 1.8 million years ago.

For Dr. Dehaene, it is the inclination to imagine — a triangle, the laws of physics, the square root of negative 1 — that captures the essence of being human. "The argument I made in the Vatican is that the same ability is at the heart of our capacity to imagine religion," he recalled recently.

He acknowledged, with a laugh, that it is no small leap from imagining a triangle to devising religion. (His own intellectual trajectory entailed a degree in mathematics and a master's in computer science before becoming a neuroscientist). Nevertheless, he said, "This is what we have to explain: Suddenly there was an explosion of new ideas with the human species."



Geometric shapes appear below the Megaloceros, a giant extinct deer, in the Lascaux, France, cave paintings, which are thought to be 17,000 years old. Alamy

An engraved slab from the Blombos Cave in South Africa, dating to 70,000 years ago. Album, via Alamy

Human or baboon?

Last spring, Dr. Dehaene and his Ph.D. student Mathias Sablé-Meyer published, with collaborators, a study that compared the ability of humans and baboons to perceive geometric shapes. The team wondered: What was the simplest task in the geometric domain — independent of natural language, culture, education — that might reveal a signature difference between human and nonhuman primates? The challenge was to measure not merely visual perception but a deeper cognitive process.

This line of investigation has a long history, yet is perennially fascinating, according to Moira Dillon, a cognitive scientist at New York University who has collaborated with Dr. Dehaene on other research. Plato believed that humans were uniquely attuned to geometry; the linguist Noam Chomsky has argued that language is a biologically rooted human capacity. Dr. Dehaene aims to do for geometry what Dr. Chomsky did for language. "Stan's work is truly innovative," Dr. Dillon said, noting that he uses state-of-the-art tools such as computational models, cross-species research, artificial intelligence and functional M.R.I. neuroimaging techniques.

In the experiment, subjects were shown six quadrilaterals and asked to detect the one that was unlike the others. For all the human participants — French adults and kindergartners as well as adults from rural Namibia with no formal education — this "intruder" task was significantly easier when either the baseline shapes or the outlier were regular, possessing properties such as parallel sides and right angles.

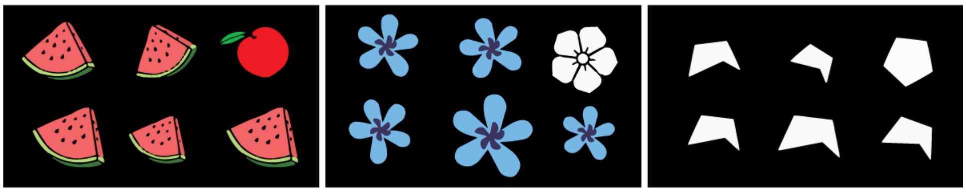
The researchers called this the "geometric regularity effect" and they hypothesized — it's a fragile hypothesis, they admit — that this might provide, as they noted in their paper, a "putative signature of human singularity." (Experiments are ongoing and open to participants online.)

With the baboons, regularity made no difference, the team found. Twenty-six baboons — including Muse, Dream and Lips — participated in this aspect of the study, which was run by Joël Fagot, a cognitive psychologist at Aix-Marseille University.

The baboons live at a research facility in the South of France, beneath the Montagne Sainte-Victoire (a favorite of Cézanne's), and they are fond of the testing booths and their 19-inch touch-screen devices. (Dr. Fagot noted that the baboons were free to enter the testing booth of their choice — there were 14 — and that they were "maintained in their social group during testing.") They mastered the oddity test when training with nongeometric images — picking out an apple, say, among five slices of watermelon. But when presented with regular polygons, their performance collapsed.

Fruit, Flower, Geometry

Symbols used to test whether baboons can pick out a non-matching symbol within a group.



By The New York Times | Source: Mathias Sablé-Meyer, Stanislas Dehaene et al.

“The results are striking, and there seems indeed a difference between the perception of shapes by humans and baboons,” Frans de Waal, a primatologist at Emory University, said in an email. “Whether this difference in perception amounts to human ‘singularity’ would have to await research on our closest primate relatives, the apes,” Dr. de Waal said. “It is also possible, as the authors argue (and reject), that humans live in an environment where right angles matter, whereas baboons do not.”

Probing further, the researchers tried to replicate the performance of humans and baboons with artificial intelligence, using neural-network models that are inspired by basic mathematical ideas of what a neuron does and how neurons are connected. These models — statistical systems powered by high-dimensional vectors, matrices multiplying layers upon layers of numbers — successfully matched the baboons’ performance but not the humans’; they failed to reproduce the regularity effect. However, when researchers made a souped-up model with symbolic elements — the model was given a list of properties of geometric regularity, such as right angles, parallel lines — it closely replicated the human performance.

These results, in turn, set a challenge for artificial intelligence. “I love the progress in A.I.,” Dr. Dehaene said. “It’s very impressive. But I believe that there is a deep aspect missing, which is symbol processing” — that is, the ability to manipulate symbols and abstract concepts, as the human brain does. This is the subject of his latest book, “How We Learn: Why Brains Learn Better Than Any Machine … for Now.”

Yoshua Bengio, a computer scientist at the University of Montreal, agreed that current A.I lacks something related to symbols or abstract reasoning. Dr. Dehaene’s work, he said, presents “evidence that human brains are using abilities that we don’t yet find in state-of-the-art machine learning.”

That’s especially so, he said, when we combine symbols while composing and recomposing pieces of knowledge, which helps us to generalize. This gap could explain the limitations of A.I. — a self-driving car, for instance — and the system's inflexibility when faced with environments or scenarios that differ from the training repertoire. And it's an indication, Dr. Bengio said, of where A.I. research needs to go.

Dr. Bengio noted that from the 1950s to the 1980s symbolic-processing strategies dominated the "good old-fashioned A.I." But these approaches were motivated less by the desire to replicate the abilities of human brains than by logic-based reasoning (for example, verifying a theorem's proof). Then came statistical A.I. and the neural-network revolution, beginning in the 1990s and gaining traction in the 2010s. Dr. Bengio was a pioneer of this deep-learning method, which was directly inspired by the human brain's network of neurons.

His latest research proposes expanding the capabilities of neural-networks by training them to generate, or imagine, symbols and other representations.

It's not impossible to do abstract reasoning with neural networks, he said, "it's just that we don't know yet how to do it." Dr. Bengio has a major project lined up with Dr. Dehaene (and other neuroscientists) to investigate how human conscious processing powers might inspire and bolster next-generation A.I. "We don't know what's going to work and what's going to be, at the end of the day, our understanding of how brains do it," Dr. Bengio said.

To know a triangle

The French mathematician René Descartes reckoned that "we could never know the geometric triangle through the one we see traced on paper if our mind had not had the idea of it elsewhere." Dr. Dehaene and Mr. Sablé-Meyer borrow this sentiment in the epigraph of a new study, currently under review, wherein they try to pin down that cognitive "elsewhere" — offering theories and empirical evidence of what "elsewhere" might be.

Building on research originating in the 1980s, they propose a "language of thought" to explain how geometric shapes might be encoded in the mind. And in a fittingly circuitous twist, they find inspiration in computers.

"We postulate that when you look at a geometric shape, you immediately have a mental program for it," Dr. Dehaene said. "You understand it, inasmuch as you have a program to reproduce it." In computational terms, this is called program induction. "It's not trivial," he said. "It's a big problem in artificial intelligence — to induce a program to do a certain thing from its input and output. In this case, it's just an output, which is the drawing of the shape."

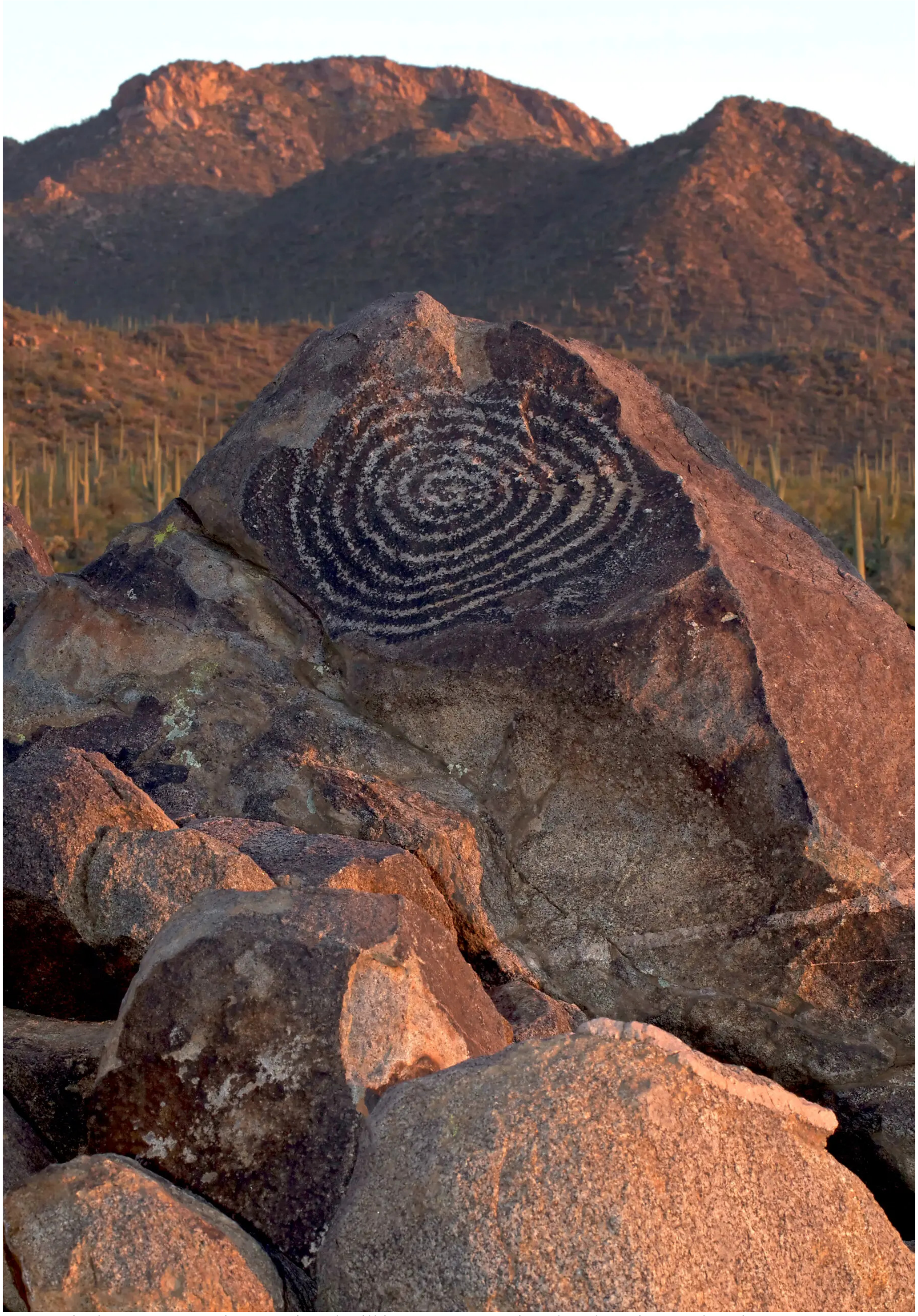
In tackling such questions, Josh Tenenbaum, a computational cognitive scientist at the Massachusetts Institute of Technology and an author of the new paper under review, likes to ask: How do we humans manage to extract so much from so little — so little data, time, energy? His approach is to solve the puzzle of these inductive leaps.

“Instead of being inspired by simple mathematical ideas of what a neuron does, it’s inspired by simple mathematical ideas of what thinking is,” he said; the distinction is one of hardware versus software, essentially. It’s an approach motivated by the British mathematician and computer scientist Alan Turing, among others, and the notion that thinking is a kind of programming.

With this new study, Dr. Dehaene and Mr. Sablé-Meyer began by proposing a programming language for drawing shapes. But the novelty, Mr. Sablé-Meyer said, wasn’t in simply proposing the language — “there must be thousands of them by now, starting with Logo in the ’60s and a whole lot of derivative turtle graphics” — but rather in devising a language that mimics our human competence for geometry.

The language is made up of geometric primitives, including basic building blocks of shapes, as well as rules that dictate how these can be combined to produce symmetries and patterns. The ultimate goal, however, in inventing such a language isn’t merely drawing, Mr. Sablé-Meyer said; it’s in developing “a good candidate theory for cognition” — a plausible theory for how thoughts, or computations, are processed in the mind.

Petroglyphs at Mount Bégo, Valley of Marvels, in southern France. Stanislas Dehaene

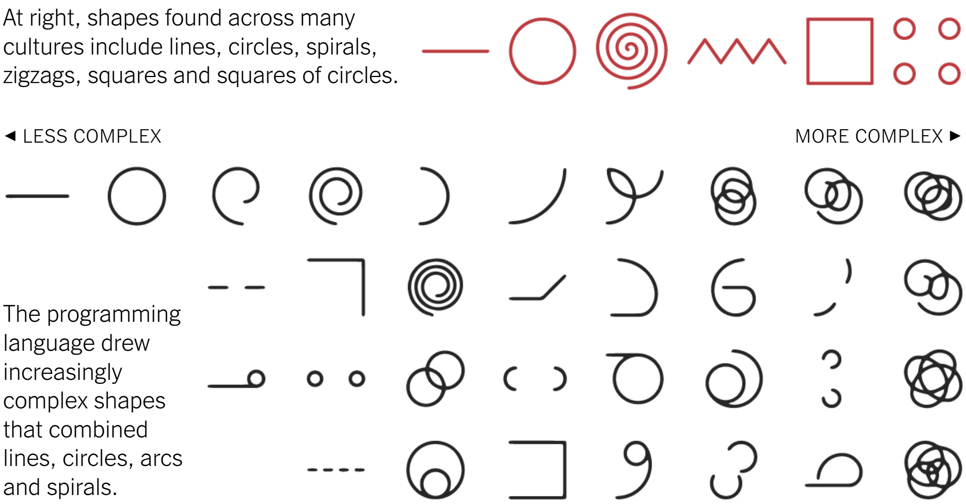


A spiral stone engraving on Signal Hill in Saguaro NationalPark, Arizona, dated 550 to 1,550 years ago. John Cancalosi/Alamy

Next the researchers used an A.I. algorithm called DreamCoder, developed a few years ago by Kevin Ellis when he was a Ph.D. student working with Dr. Tenenbaum; he is now a computer scientist at Cornell University and an author of the new study. DreamCoder modeled how the mind might use the programming language in optimally processing shapes: the algorithm finds, or learns, the shortest possible program for any given shape or pattern. The theory is that the mind operates in much the same way.

Geometric Language

Researchers developed a programming language to generate shapes of increasing complexity. The theory is the brain similarly encodes shapes as programs in a language.



By The New York Times | Source: Mathias Sablé-Meyer, Stanislas Dehaene et al.

The researchers then added humans back into the equation, by testing the ability of subjects to process shapes of varying complexity that the programming language had generated. During one test, they measured how long it took people to memorize a shape such as a squiggly curve, compared with how long it took to find that shape among a collection of six similar squiggles (called the match-to-sample test). The researchers found that the more complex a shape and the longer the program, the more difficulty a subject had remembering it or discriminating it from others.

The baboons are trying this test now. But beyond these behavioral studies, the researchers hope to probe even deeper into symbolic thought — at Dr. Dehaene's NeuroSpin neuroimaging lab, with functional M.R.I.s that measure neural activity while subjects entertain geometric confections. Dr. Dehaene already has some data showing that the brain regions involved — in the prefrontal and parietal lobes — overlap with those known to be associated with the human "number sense."

The brain areas that light up for the language of geometry are what Dr. Dehaene and his former Ph.D. student, Marie Amalric, now a postdoctoral fellow at Harvard, called the math-responsive network. “They are very different from the classical regions activated by spoken or written language, such as Broca’s area,” he said.

Language is often assumed to be the quality that demarcates human singularity, Dr. Dehaene noted, but perhaps there is something that is more basic, more fundamental.

“We are proposing that there are languages — multiple languages — and that, in fact, language may not have started as a communication device, but really as a representation device, the ability to represent facts about the outside world,” he said. “That’s what we are after.”

A version of this article appears in print on , Section D, Page 1 of the New York edition with the headline: Decoding Shapes

The Curious World of Mathematics

- Pi, the famous ratio that is estimated to more than 22 trillion digits (and counting), is the perfect symbol for our long effort to tame infinity.
- Celebrate Pi (or Pie) Day everyday. Dr. Eugenia Cheng spreads the magic of numbers through dessert recipes.
- What is the sum of an infinite series of natural numbers? The answer may be smaller than you think.
- A Texas oil heir was fascinated with one of math’s greatest enigmas: Fermat’s theorem. His private support may have been a critical factor in the puzzle’s solution.