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FEATURE ARTICLE

The Uniqueness of Human Recursive Thinking

The ability to think about thinking may be the critical attribute that distinguishes us from all other species

Michael Corballis

On a visit to Kyoto once, I encountered a gate with a posted sign written in Kanji. I asked the guide what it meant, and he replied that it could be translated as "Post no bills." One need only be moderately astute to realize that the sign itself is a bill and so violates its own message. To prevent such bills from being posted, we might consider posting another sign that says, "Post no 'Post no bills' bills." But this in turn is a bill, so perhaps we need another sign that says, "Post no 'Post no "Post no bills" bills' bills." The problem, as I'm sure you now see, is that this process leads to an infinite sequence of signs that would not only cover the gate, but eventually the entire universe, since each bill is longer than the last. Better, perhaps, just to allow people to stick a few bills on the gate.

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The self-referential bills are examples of recursion. Another instance comes from an anonymous parody of the first line of Edward Bulwer-Lytton's infamous novel, *Paul Clifford*:

> It was a dark and stormy night, and we said to the captain, "Tell us a story!" And this is the story the captain told: "It was a dark and stormy night, and we said to the captain, 'Tell us a story!' And this is the story the captain told: 'It was a dark....'"

In computational terms, recursion is a process that *calls* itself, or that calls a similar process. In the example of "Post no bills," the sign is, albeit unwittingly, referring to itself, whereas in the parody of Bulwer-Lytton's novel, the story in the story is the same story.

Alternatively, one can put the definition in dictionary style:

recursion (ri-kûr'-zhən) *noun.* See **recursion.**

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Perhaps it is best not to dwell on this.

I propose that recursion is a ubiquitous property of the human mind and possibly the principal characteristic that distinguishes our species from all other creatures on the planet. Recursion is a well-known property of language, but I shall argue that the phenomenon applies to a number of other putatively human domains, including "theory of mind," mental time travel, manufacture, the concept of self and possibly even religion.

Language

Grammatical rules in language exploit recursion to create the infinite variety of potential sentences that we can utter and understand. Perhaps the simplest example is a sentence that is composed of sentences, according to a rule that might be expressed as

S ? S + S

where the arrow is a symbol for *can be rewritten as,* and *S* stands for *sentence*. Rewrite rules of this form are a conventional way to show how language is constructed. This particular rule, invoked twice, creates the following sentence, found in A. A. Milne's *Winnie the Pooh*: "It rained and it rained and it rained." This example, though, is rather trivial, since it simply amounts to repetition, presumably to create a sense that it rained for rather a long time, causing Piglet some ennui.

Recursion can be much more complex than simple repetition, and it is used in human language to provide qualification or to add complexity to an utterance. For example, we can break sentences down into phrases, and then apply recursive rules to tack phrases onto phrases, or embed phrases within phrases. There are noun phrases (NP), verb phrases (VP) and prepositional phrases (PP).

On a visit to a publishing house in Hove, England, I was greeted by the publisher with the unlikely sentence "Ribena is trickling down the chandeliers." (Ribena is the brand name of a flavored drink in the United Kingdom, and it was indeed dripping off the light fixtures.) Here, the sentence is first broken down into an NP ("Ribena") and a VP ("is trickling down the chandeliers"). But the VP is itself composed of a verb ("is trickling") plus a PP ("down the chandeliers"), which in turn is composed of a preposition ("down") plus an NP ("the chandeliers"). The sentence can therefore be parsed in terms of the following rewrite rules:

1. S ? NP + VP
2. NP ? noun
3. VP ? verb + PP
4. PP ? preposition + NP

Applied to more complex sentences, such rules involve recursion. For example, an NP may include aPP*,* which may in turn include an NP*.* In principle, one could cycle repeatedly through rules 2 and 4. Had the publisher not been in something of a panic, he might have elaborated: "Ribena is trickling down the chandeliers onto the carpet beside my desk." (There was a nursery upstairs).

Children quickly learn to appreciate the power of recursion (if not of Ribena), as illustrated by these sentences from the well-known children's story, "The House That Jack Built":

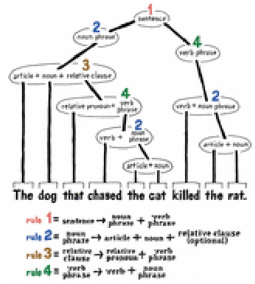
1. This is the house that Jack built.
2. This is the malt that lay in the house that Jack built.
3. This is the rat that ate the malt that lay in the house that Jack built.

4. This is the cat that killed the rat that ate the malt that lay in the house that Jack built.

5. This is the dog that worried the cat that killed the rat that ate the malt that lay in the house that Jack built.

And so it goes on. It is important to understand that this is not simply a matter of adding disconnected elements. New sentences are added progressively at the beginning, and the rest of the sentence increasingly qualifies the noun. In the fourth sentence, for example, the cat in question is precisely the one that killed the rat that ate the malt, and so on. A cat that killed a rat that did not eat the malt that lay in the house that Jack built simply will not do.

The sentences in "The House that Jack Built" are examples of what is called *end recursion*, in which the recursive rule is invoked at the end. The fourth sentence, for example, begins with the sentence "This is the cat," but then the relative clause "that killed the rat" is added to qualify the cat. This relative clause mentions a rat, and a further relative clause, "that ate the malt," is added to qualify the rat, and so forth. In principle, recursive elements can be added *ad infinitum*or until your short-term memory can hold no more.



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Another kind of recursion is *center-embedded recursion*, in which constituents are embedded within constituents. For example, in the third sentence of "The House That Jack Built," one might wish to make the malt rather than the rat the subject of the sentence, and so embed a relative clause describing the malt into a sentence about the malt: *The malt that the rat ate lay in the house that Jack built.*

Such embedded phrases, as in this very sentence, are common. But if phrases are embedded in embedded phrases, things can get complicated. For example, let's convert the fourth sentence into one featuring the malt: *The malt that the rat that the cat killed ate lay in the house that Jack built.* Now try the fifth sentence: *The malt that the rat that the cat that the dog worried killed ate lay in the house that Jack built.* Are you still following me?

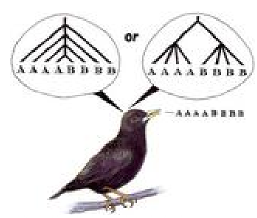
That last example is perfectly grammatical, but more than one level of center-embedded recursion is hard to follow, for psychological rather than linguistic reasons. Center-embedding requires a memory device, such as a stack of pointers, indicating where to pick up the procedure once an embedded constituent has been completed. This is not so bad if there is just one embedded structure, since a single pointer can be held in memory to show where to pick up the original procedure. With multiple embedding, you need to keep track of several pointers, which can overstretch working memory. Examples of sentences with more than one level of center-embedding are rare in natural discourse.

In a recent *Science* article, psychologist Marc D. Hauser of Harvard University and his colleagues suggested that recursion is a basic characteristic that distinguishes human language from all other forms of animal communication. Chimpanzees and bonobos have been taught a form of language, sometimes known as *protolanguage,* with some of the characteristics of human language, including the use of symbols to represent objects or actions, and some ability to combine symbols to create new meanings. There is no evidence, though, that these apes use these symbols (or combinations of symbols) in recursive fashion, to create anything like the unlimited set of meanings that we humans can create.

What About Birds?

Superficially, at least, the songs emitted by some birds seem to have something of the complexity of human language. American ornithologists Jack P. Hailman and Millicent S. Ficken once argued that chickadee calls have a computable syntax and therefore qualify as "language." These calls are made up of four qualitatively distinct sounds, which we may label *A, B, C* and *D*. These elements are always in the same order, although any element may be repeated any number of times or may be omitted altogether. The sequences *ABCD, B, BD, AAABBCCCD* are all legitimate. Although there is considerable variety in such sequences, they do not involve recursion beyond the simple repetition of elements. Unlike human language, the sequences can be specified by what is known as a *finite-state grammar*, in which the choice of element at any point in the sequence can be specified by the preceding element. Thus *B* may follow *A,* or *B* may be the first in the sequence, but it can never follow *C* or *D*. Of course, the birds may well have used more complex rules, but we do not need to suppose more than that they merely stepped from one element to the next, without any appreciation of what went before or what comes after. In contrast, human language involves the combining of constituents into phrases, and the generation of sentences by recursive rules whereby phrases may be defined in terms of phrases, and every element in the sequence contributes to the grammatical construction.

Neuroethologist Timothy Q. Gentner at the University of California, San Diego, and his colleagues have recently argued that European starlings can parse sequences of sounds consisting of as many as four levels of center-embedded recursion. The starlings were taught to identify sequences of sounds, drawn from eight sounds classified as rattles, *A,* and eight classified as warbles*, B*. The sequences were generated either by a finite-state grammar in which *AB* sequences were simply repeated up to four times (as in *AB, ABAB, ABABAB* or *ABABABAB*), or in which *AB* pairs are embedded in *AB* pairs with up to four levels of recursion (as in *AB, AABB, AAABBB,* and *AAAABBBB*). The actual choices of *A*s and *B*s were generated randomly, so that the birds could not simply learn particular sequences. Some, but not all, of the birds learned to discriminate these kinds of sequences from each other, and also from sequences that did not obey the rules, suggesting a capacity to understand recursion.



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The problem here is that the starlings need not have parsed the recursive sequences according to the recursive rule. A simpler solution is simply to count the number of successive *A*s and the number of successive *B*s, and accept the sequence as belonging to the recursive category if the two numbers are equal. Such a strategy is probably not beyond the computational capacity of a starling. There is abundant evidence for a number sense in birds. For example, the famous African gray parrot, Alex, raised by Irene Pepperberg of Harvard University, can count up to six and understands the concepts of same and different. Starlings are also known for their intricate songs, suggesting sophisticated production and perception of sequences. The final movement of Mozart's Piano Concerto in G Major, K. 453, is said to be based on a song by his pet starling. There is no suggestion, though, that the songs of starlings, although Mozartian, are recursive. It should also be remembered that even humans have considerable difficulty parsing sentences in which the number of embedded phrases exceeds two.

Again, we do not know what really goes on in the mind of a starling, but parsimony dictates that we accept the simpler explanation for their behavior. The challenge to show that any nonhuman species can either produce or parse recursive combinations of elements remains.

Theory of Mind

Recursion is not restricted to language but applies to other aspects of human thought. One of these is known as "theory of mind," which refers to the ability to imagine what might be going on in the mind of another individual. The mental processes of thinking, knowing, perceiving or feeling might be regarded as zero-order theory of mind, and are probably common to many species. They are not recursive. First-order theory of mind refers to thinking, knowing, perceiving or feeling what *others* are thinking, knowing, perceiving or feeling, and therefore is recursive. It is implied by statements such as "I think you must be thinking that I'm an idiot," or "Ted thinks Alice wants Fred to stop bugging her."

Are nonhuman species capable of this? How could we know? The problem is that language itself is well designed to express recursive ideas, and it is difficult to test theory of mind without language. So far, no nonhuman animal has shown us that it has a communication system powerful enough to reveal theory of mind, so we must rely on nonlinguistic tests.

One such test involves tactical deception, where one animal performs some act based on an appreciation of what another animal might be thinking, or what it might be able to see. A young chimpanzee might wait until a dominant male is not looking before stealing food. In a more complex example, a young male baboon may see another baboon eating corn. He screams in mock fear, and his mother comes and chases the other baboon away. The young baboon then seizes the corn. The question here is whether the young baboon actually knew what would be in his mother's mind when he screamed or whether the behavior had simply been learned through trial and error.

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Psychologists Richard Byrne and Andrew Whiten at the University of St. Andrews in Fife, Scotland, collected examples of possible tactical deception from observations made by primatologists in the field and carefully filtered out those that might depend on simple trial and error. From a total of 253 cases only 26 observations passed the test. There were 12 examples from common chimpanzees and three each from bonobos, gorillas and orangutans. Five more instances from mangabeys, which are closely related to baboons, also passed. Nevertheless, Byrne and Whiten suggested that true tactical deception, requiring theory of mind, might be restricted to human beings and great apes, and even among the latter the evidence is not very compelling. In marked contrast, a search for "tactical deception" on the Google search engine results in roughly 967,000 responses, most of them relating to human warfare.

Other tests have been proposed for nonhuman species, but the results are scarcely more compelling. For example, psychologist Daniel Povinelli and his colleagues at the University of Louisiana, Lafayette, have shown that chimpanzees are as likely to beg for food from a person who is blindfolded, or who has a bucket over her head, as they are from one who can see, suggesting that the chimps are incapable of the recursive understanding of whether another individual can see. Michael Tomasello at the Max Planck Institute for Evolutionary Anthropology and his colleagues argue that chimpanzees are actually smarter than that and under some circumstances do understand what others can see, although the authors do acknowledge that "chimpanzees do not have a full-blown, human-like theory of mind."

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If there is doubt over whether great apes are capable of first-order theory of mind, there is certainly nothing to suggest that they are capable of higher orders. Human affairs run easily into many orders of theory of mind, as is well conveyed in literature and the theater. In Jane Austen's *Pride and Prejudice*, Elizabeth Bennet *thinks* that Darcy *thinks* that she *thinks* he *thinks* too harshly of her family. Or in Shakespeare's *Twelfth Night*, Maria *foresees* that Sir Toby will eagerly *anticipate* that Olivia will *judge* Malvolio absurdly impertinent to *suppose* that she *wishes* him to *regard* himself as her *preferred* suitor. Each italicized word after the first indicates another level of recursion.

Theory of mind may even be a prerequisite for religious belief, according to evolutionary psychologist Robin Dunbar at the University of Liverpool. The notion of a God who is kind, who watches over us, who punishes and who admits us to Heaven if we are suitably virtuous depends on the understanding that other beings—in this case a supernatural one—can have human-like thoughts and emotions. Indeed, Dunbar supposes that several orders of recursion may be required, since religion is a social activity, which depends on shared beliefs.

The recursive loop that is necessary runs something like this: I *suppose* that you *think* that I *believe* there are gods who *intend* to influence our futures because they *understand* what we *desire*. This is fifth-order recursion. Dunbar himself must have achieved sixth-order recursion if he supposes all this, and if you suppose that he does then you have achieved seventh-order recursion. Call it "Seventh Heaven," if you like.

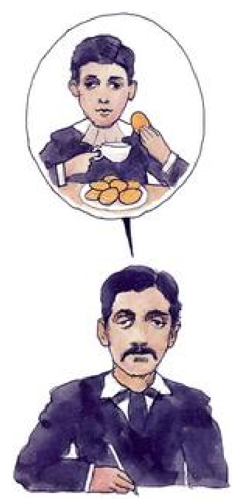
The Self and Mental Time Travel

The belief that one has thoughts of one's own is theory of mind about one's self. Philosopher René Descartes is famous for the phrase "*cogito, ergo sum,"* although what he actually wrote was "*Je pense, donc je suis"*—"I think, therefore I am." Descartes took this as the basic proof of his own existence, because even if he doubted it, doubt was a form of thinking, so his actual existence was not in doubt. The phrase is fundamentally recursive, since it implies not just thinking, but thinking about thinking. The fact that we can be aware of our own thinking (and not just of our own thoughts) implies a concept of self.

One way to investigate whether animals have a concept of self is the mirror test, first devised in 1970 by psychologist Gordon G. Gallup Jr., now at The State University of New, York at Albany. A mark is placed on the animal in such a way that it can only be viewed in a mirror. The question then is whether the animal will attempt to remove the mark, or otherwise indicate that it realizes the mark is on its own body. The evidence suggests that only dolphins, great apes and elephants pass the test, which has been taken to mean that they have a concept of self. The results are controversial, though, because it might mean no more than that these animals understand that the object in the mirror corresponds to their own *physical self,* but need not mean that they understand that the physical self is capable of thoughts or desires.

To be properly recursive, the concept of self should be involved—that is, not merely knowing that one is a physical object, but knowing that one knows, or knowing that one has mental states. There is little evidence that shows this to be the case for any nonhuman species.

Another way to test the concept of self is through the awareness that one can exist at different points in time. For example, we might remember what we were thinking or experiencing yesterday, which is again a recursive process. It indicates that we can not only understand that we have thought processes in the present, but that we also had them in the past and will have them in the future. To extend Descartes' dictum, we might say "I thought, therefore I was," and "I will think, therefore I will be." The concept of self can be extended through time.



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The notion of a past self depends on memory. There are two kinds of conscious memory, according to the Canadian neuroscientist Endel Tulving. *Semantic memory* refers to your storehouse of knowledge about the world, such as knowing that Wellington is the capital of New Zealand, or that the boiling point of water is 100 degrees Celsius. *Episodic memory* refers to the particular episodes in your life that you can relive in your mind. You probably remember what you did yesterday, not just as a succession of facts, but as events that you can bring to consciousness and replay in your mind. Such memories, unlike semantic memories, are recursive because they involve making mental reference to your earlier mental self. Recovery of semantic memories implies what Tulving calls *noetic awareness*, which is simply knowing, whereas the recovery of episodic memories implies *autonoetic awareness*, which is self-knowing.

Tulving has also claimed that episodic memory is unique to humans. This is not to deny that other species have memories, often prodigious ones. Among birds that cache food, for example, the Clark's nutcracker is among the most prolific, storing seeds in thousands of locations and recovering them with high, but not perfect, accuracy. This does not mean, though, that the bird remembers the act of caching the food itself; rather, it may simply remember where the food is located. I believe I know the meanings of tens of thousands of words, but with very few exceptions I cannot remember the episodes in which I first encountered these words.

Clever experiments by Nicola Clayton and her colleagues at the University of Cambridge have suggested that at least one species of bird, the Western scrub-jay, may have more detailed memory than one might have imagined. The birds can remember where they have stored particular items, such as worms or nuts, and they will recover one or the other depending on how long they have been cached. They generally prefer worms, but they will avoid the nightcrawlers in favor of nuts if the worms have been cached for too long, and are therefore likely to have decayed and become unpalatable. This has been taken to mean that the jays know *what* has been cached, *where* it has been cached and *when* it was cached. These three conditions, known as the *WWW criteria,* have been claimed by some to be sufficient evidence for episodic memory in the scrub-jay—a humbling thought. Even so, this may not be sufficient proof that the birds relive the act of caching. The memory for where a food item has been cached might carry a time tag, equivalent to a "use-by date," which indicates how long the item has been cached, but this need not involve a specific memory for the caching episode itself.

One might stand a better chance of demonstrating mental time travel in primates than in birds, especially in our closest nonhuman relatives, the chimpanzee and the bonobo. The German-American psychologist Wolfgang Köhler, who is famous for his experiments on chimpanzees while stationed in the Canary Islands during World War I, noted that, for all their improvisational skills, chimpanzees had little concept of the past or the future. Work over the past 50 years on teaching language-like communication to chimpanzees and bonobos provides little reason to question this conclusion. So far, there is no evidence for the acquisition of tense, nor any sense that these animals communicate about specific past events or possible future ones.

Psychologist Thomas Suddendorf at the University of Queensland has argued that episodic memory is but one part of a more general capacity for *mental time travel*, which includes travel into an imagined future as well as into the recalled past. Amnesic patients who lose episodic memory also lose a sense of possible future events, and children seem to understand the concepts of past and future at about the same time, around age four. Indeed, episodic memory may function as not so much a record of the past as a repository of information about events that can supply a kind of vocabulary for the generation of future events. Perhaps this explains why episodic memory is both unreliable and incomplete, and often a bane to courts of law. In cases of amnesia, it is typically episodic rather than semantic memories that are lost. It does not matter that episodic memory is incomplete and fragile, so long as it supplies sufficient information to generate plausible and effective future scenarios. After all, it is the future that matters to us, not the past.

It is perhaps not an exaggeration to say that human beings are obsessed with time, as we ponder the past and plan our futures. We measure time in seconds, minutes, hours, days, weeks, months, years, decades, centuries, millennia, eras and eons. We measure it both back to the past and forward to the future. We extrapolate it beyond our own life spans, even back to the Big Bang, which is said to have created the universe. Through time we understand death, and perhaps because of this we have appealed to religions for the promise of an afterlife. Time creates stress, as deadlines draw near, but we can also appeal to time to heal our woes. When Viola in *Twelfth Night*, masquerading as a man, finds herself in an impossible situation, she is moved to say, "O Time, thou must untangle this, not I; It is too hard a knot for me t'untie!"

Language itself is infused with time. We use many prepositions, such as *at*, *about*, *around*, *between*, *across*, *against*, *from*, *to* and *through*, to apply to time as well as space, and some, such as *since* or *until*, are restricted to the time dimension. The use of tense allows us to incorporate time into language, even in recursive fashion. For example, the past perfect, as in "I had already eaten," refers to an event that is further in the past than some reference time in the past, while the future perfect, as in "He will have arrived," refers to something that will be in the past at some future date.

Whatever the capacity for nonhuman animals to travel mentally in time, it seems safe to say that once again the generative, recursive way in which we imagine events in time seems to surpass anything that has been demonstrated, or even hinted at, in our closest primate relatives.

Counting and Tools

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Another example of recursion, probably derived from language, is counting. By using recursive rules, humans can count indefinitely. All you need is a finite set of digits and a few simple rules that you can use to progress from one number to the next. We now know that many animal species can count, but they can only do so accurately up to some small value. Even that is not strictly counting but is closer to the human capacity for *subitization,* which is the ability to enumerate at a glance quantities up to about four. Beyond that, our ability to enumerate without actually counting is increasingly inaccurate as the actual number increases. You might estimate the number attending a lecture as around 75, or the crowd at a football game as 15,000, but in neither case are you likely to be accurate. Counting, though, can lend perfect precision up to any number —although it can of course be time-consuming. Counting is a further illustration of how recursive principles can vastly increase the power and capacity of the human mind. More generally, human computation is recursive. Programmers use subroutines that call subroutines, and my laptop contains folders that contain folders that contain folders.

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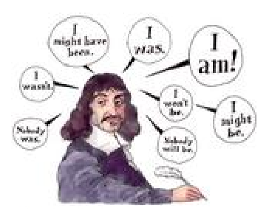
The use and manufacture of tools may also include recursive components. Tool use itself is not uniquely human. Chimpanzees use stones to crack nuts and twigs to extract termites from their holes; they even fashion "spears" to stab prey. Capuchinmonkeys are exceptional tool users, using objects in a variety of ways to achieve their own ends. They use sticks to rake in food, stack boxes to reach food and even throw objects at people. New Caledonian crows strip and shape pandanus leaves, or fashion twigs with hooks on the end, to extract grubs from holes. But human beings are surely the most prodigious makers and users of tools. The American comparative psychologist Benjamin B. Beck, an expert on tool-making behavior, once remarked that "man is the only animal that to date has been observed to use a tool to make a tool." This again implies recursion. Modern technology is at least repetitive, if not always truly recursive; consider the assembly lines that began with the Model T Ford. Nevertheless there are wheels within wheels, engines within engines, computers within computers. Ultimately, perhaps, we may swamp the globe with the products of our recursion.

Evolving the Recursive Mind



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Human beings may well be unique in our attempts to find criteria that define our own uniqueness—we think uniquely, therefore we are unique. Among the characteristics that are often claimed as uniquely human are language, theory of mind, the concept of a knowing self, episodic memory, mental time travel, making tools that make tools and counting. All, I submit, are unique because of the human capacity for recursive thought.

Evolutionary psychologists maintain that the essential characteristics of the human mind evolved during the Pleistocene, the period from about 1.8 million years ago until around 10,000 years ago. During this era, our hominin forebears were hunter-gatherers, and social bonding and communication became essential to survival. According to evolutionary psychologists, such as Leda Cosmides and John Tooby at the University of California, Santa Barbara, the mind evolved in modular fashion, with specific modules dedicated to specific functions, such as language, theory of mind, cheater detection and romantic love. Because recursion applies to several domains, it is unlikely that the phenomenon comprises a module in the sense that evolutionary psychologists use the term. I suggest rather that it is a mode of computation that can be applied to several different mental domains.

From around two million years ago, and through the Pleistocene, the brains of our hominin forebears increased dramatically in size, to become about three times as large as expected in a primate of the same bodily size. American zoologist Richard D. Alexander has suggested not only that social bonding was necessary to ensure survival in a hostile environment (shared with killer cats and other dangers), but also that our forebears faced increasing competition from their own kind. This led to runaway cycles of Machiavellianism countered by social bonding and mechanisms for the detection and expulsion of freeloaders, leading to such complex but fundamentally social phenomena as language, theory of mind, religion and wars. It was this complex calculus of social affairs that may have led to the selection for larger brains with the capacity for recursive neural systems.

The expansion of the frontal lobes, in particular, may have been especially critical. The frontal lobes are known to be involved in language, theory of mind, episodic memory, and mental time travel, and these recursive faculties may also depend on the fact that humans, relative to other primates, undergo a prolonged period of growth. To conform to the general primate pattern, human babies should be born at around 18 months, not 9 months.

But, as any mother will know, this would be impossible given the size of the birth canal. The brain of a newborn chimpanzee is about 60 percent of its adult weight, whereas the brain of a newborn human is only about 24 percent. Our prolonged childhood means that the human brain undergoes most of its growth while exposed to external influences, and so is finely tuned to its environment.

Patricia M. Greenfield of the University of California, Los Angeles, has documented how children develop hierarchical representations for both language and the manipulation of objects at around the same time. Just as they begin to combine words into phrases and then use those phrases as units to combine into sentences, so they begin to combine objects, such as nuts and bolts, and then use the combinations as objects for further manipulation. Greenfield argues that both activities depend on a region corresponding to Broca's area, that part of the cerebral cortex primarily responsible for the production of language, on the left side of the brain. She goes on to suggest that this relation between language and hierarchical manipulation persists into adulthood, citing evidence that people with Broca's aphasia are also poor at reproducing drawings of hierarchical tree structures composed of lines.

In the further course of development, though, the frontal-lobe structures involved in recursion may differentiate. Greenfield also refers to evidence that, in a sample of mentally retarded children, some were skilled in hierarchical construction but deficient in grammar, whereas others showed the reverse pattern. She relates these findings to neuro-physiological evidence that the same brain area may be involved equally in both functions up to the age of two. Beyond that age there is increasing differentiation in the vicinity of Broca's area, such that an upper region is involved with the physical manipulation of objects and an adjacent lower region organizes grammar.

Greenfield's analysis may be widely applicable, pertaining to the growth and differentiation of a number of recursive skills, including language, theory of mind, episodic memory, the understanding of time and object manipulation. All of these skills seem to emerge early in childhood, at a time when the brain is growing. The critical period of postnatal growth is both an evolutionary and a developmental phenomenon. It probably began to appear as a characteristic of the genus *Homo* some two million years ago and governs the way children acquire skills. This extended growth pattern takes us beyond simple associative networks toward more dynamic processors that can parse hierarchical structures and use rules recursively.

Although recursive skills appear to be somewhat dissociable, their co-development, and perhaps co-evolution, may be linked. For example, the emergence of recursive syntax may have been evolutionarily selected precisely because it maps onto the recursive structure of theory of mind and allowed our ancestors to communicate their Machiavellian thoughts—no doubt to their accomplices, not their rivals. Theory of mind may be involved in a different way in language, allowing us to modulate our speech in conformity with the mental state of the listener. The recursive understanding of time may have been critical to the evolution of language itself, which is exquisitely equipped to recount events at different points in time, and at locations other than the present one. Recursion, then, is a property that infuses the early development of basic skills, providing us with the flexibility and creativity that characterizes the human mind.

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