

The Information Animal and the Super-Brain

John F. Hoffecker¹

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¹Institute of Arctic and Alpine Research, University of Colorado at Boulder, 1560 30th Street, Campus Box 450, Boulder, Colorado 80309-0450 USA; Phone: 303-735-7804; FAX: 303-492-6388; e-mail: John.Hoffecker@colorado.edu

Abstract. Analogous to a super-organism, a super-brain is defined as a group of interacting brains that collectively exhibit at least some of the characteristics of an individual brain. Among eusocial animals, a super-brain evolved in the context of the super-organism (i.e., product of kin selection), but humans apparently evolved a means of brain integration through reciprocity, permitting formation of co-operative networks among non-relatives. It is suggested here that reciprocal alliances emerged primarily as a consequence of an “information-center” foraging strategy among early humans, analogous to that of the honeybee colony. Later increases in human brain size probably reflect significant expansion of gathered and stored information. With syntactic language, modern humans developed a more fully integrated super-brain that mirrors the flow of information within an individual brain and exhibits the property of generativity.

Key words: neuroscience & archaeology; evolutionary ecology

Thomas Hobbes, a thinker who helped define the modern age, may have been the first to draw a parallel between human society and an individual person (Dyson 1997, pp. 1–13). In his controversial *Leviathan*, Hobbes likened the various aspects of seventeenth-century European society to the functioning parts of the human body—magistrates as joints, criminal justice system as nerves, counselors as memory, and so forth—joined together like an “artificiall man . . . a reall unities of them all, in one and the same person” (Hobbes 1968, p. 81).

Hobbes noted both the parallels and contrasts between the societies of humans and the societies of insects such as ants and bees, which he characterized as “political creatures” (Hobbes 1968, p. 226). While ants and bees exhibit some of the organizational characteristics of complex human societies, they lack the internal conflicts of the latter—the constant debates and disagreements over whose plan should be followed and which laws should be enforced.

Insect societies have since been characterized as an organizational level in biology above that of the individual organism or a “super-organism” (e.g., Wheeler 1928; Maynard Smith and Szathmáry 1995, pp. 257–270). Human societies do not meet the criteria of a super-organism, however; the parallels they exhibit with insect societies have a different basis, and archaeology has a role to play in explaining it.

The Super-Brain: Levels of Integration

The concept of a *super-organism* was proposed at the beginning of the twentieth century by the entomologist William Morton Wheeler (1911, 1928), who argued that an ant colony be considered a form of organism. An ant colony, he noted, functions as a unit, experiences a life cycle of growth, and is divided into reproductive and non-reproductive components (i.e., sterile casts). The super-organism concept may also be applied to bees, wasps, and termites, all of

which are considered *eusocial* or “true social” insects (Wilson 1971). Among vertebrates, eusociality is known only in two genera of African mole-rats (Bennett and Faulkes 2000).

The super-organism concept fell out of favor for some years, but has been revived in recent decades by students of the social insects (e.g., Wilson 1971; Seeley 1989), who identify three criteria of eusociality: “. . . first, its adult members are divided into reproductive castes and partially or wholly nonreproductive workers; second, the adults of two or more generations coexist in the same nests; and third, nonreproductive or less reproductive workers care for the young” (Hölldobler and Wilson 2009, pp. 8–9). Students of the super-organism distinguish various degrees or levels of eusociality on a spectrum of variation (see Hölldobler and Wilson 2009, pp. 9–10).

A *super-brain* may be defined as two or more individual brains that collectively perform at least some of the functions of a single brain. The concept is analogous to that of the super-organism, but applies to an organ and not an organism. The animal brain evolved more than half a billion years ago; its function is to acquire information about the environment and to initiate appropriate responses to detected variations in the external world (e.g., Allman 1999; Striedter 2005). Although some simple organisms such as the bacterium *E. coli* possess structures that perform this function in limited ways (Swanson 2003), the metazoa—beginning with the phylum Cnidaria (jellyfish, sea anemones, and others)—evolved a specialized cell (neuron) and organ for information processing.

An example of super-brain function may be found among honeybee swarms, which collectively decide on a new nest site on the basis of information gathered by and shared among members of the swarm (Lindauer 1955; Seeley 2010). An essential component of the super-brain is a *means of integration*: information must move from one individual brain to another for

collective brain function. And, as there are different levels of eusociality, there also is a spectrum of variation with respect to the degree of super-brain integration.

The largest known super-organisms are found among the ants, especially the leafcutter ants of the genus *Atta*. Colonies of *A. sexdens*, for example, may number as many as 5–8 million individuals (Hölldobler and Wilson 2009, pp. 426). Leafcutter ants forage collectively over relatively large areas, and they are especially striking in their cultivation of fungus gardens (located in specific chambers within their vast underground nest complexes) and in their numerous specialized labor castes, which include leaf-fragment carriers, gardeners, soldiers, road maintenance workers, and many others (Hölldobler and Wilson 2011, pp. 51–75); one species of American leafcutters contains a caste of corpse-removal specialists or undertakers (Hölldobler and Wilson 2009, pp. 116). The foraging strategy requires a nearly constant stream of communication among individual ants. Communication is largely based on the release of chemical compounds (i.e., odor), but also entails vibratory sound or *stridulation* (Hölldobler and Wilson 2011, pp. 77–88).

Although ants possess the largest super-brain (outside modern humans), because of the immense size of the colonies among some taxa (i.e., individual ant brain = ~1 million neurons x 5–8 million individual ants [Hölldobler and Wilson 2011, pp. 77–80]), an ant super-brain exhibits relatively limited integration. This is despite the sophistication of their communication system. Because ants are sensitive to very subtle variations in chemical compounds, they can communicate by synthesizing and combining the molecules of various compounds in a manner analogous to the construction of words and sentences (see Hölldobler and Wilson 2009, pp. 179–183). And this also is despite the fact that some ants map their environment with visual cues (see Hölldobler and Wilson 2009, pp. 118).

Although learning and memory play a role in ant behavior, the ant super-brain is integrated primarily on the genetic level. The hierarchically organized maps created by some ants are not transmitted as representations from one brain to another. Instead, ants use their multimodal communication system to transmit *signals* that elicit genetically programmed responses among the various specialized labor castes (i.e., signals that function as sensory input) (see Hauser 1996, pp. 6–10); they employ a relatively large number of signals (e.g., fire ants employ 20 different chemical signals [Hölldobler and Wilson 2009, pp. 181]).

For comparative purposes, I have termed the type of super-brain found among ant colonies “Type 0” (see Table I). This form of super-brain—characterized by limited flow of information among individual brains—seems to be common among eusocial species, and it is the more highly integrated form of super-brain that is rare. In fact, some degree of brain integration—a Type 0 super-brain—also is found among various non-eusocial taxa (i.e., outside the context of a super-organism). For example, vervet monkeys have developed several alarm calls among groups that are coded for specific predators (Cheney and Seyfarth 1990). As in the case of the signals transmitted by ants, the calls function as sensory input from one brain to another, but do not communicate hierarchically organized representations. The emergence of brain integration—even a low level of integration—in non-eusocial groups is pertinent to the problem of super-brain evolution in humans.

A Type 0 super-brain appears to have evolved among the only known eusocial vertebrates—African mole-rats. The naked mole-rat (*Heterocephalus glaber*) inhabits arid regions of East Africa in colonies that average about 80 individuals (although colonies composed of almost 300 individuals have been reported) (Bennett and Faulkes 2000, pp. 90–93; Faulkes and Bennett 2007). Naked mole-rats forage for tubers underground by excavating lengthy

burrow systems. The dispersed, clumped, and unpredictable distribution of tubers in their arid habitat imposes high risks on solitary foraging. These risks are minimized by cooperative foraging—individual mole-rats lay down odor trails and recruit colony mates to food sources with a variety of vocalizations (Bennett and Faulkes 2000, pp. 242–244). Once again, the vocalizations—which are highly diverse for mammals—function as signals and sensory input.

A more highly integrated super-brain is found in the honeybee (*Apis mellifera*), justifiably famous for its dance “language” (von Frisch 1993; Riley et al. 2005). Honeybees forage over a relatively large area (relative to their body size), gathering pollen (protein source), nectar (carbohydrate source), water, and propolis (resin used as raw material). In order to cope with seasonal variability in resource availability, honeybees in the temperate zone store substantial amounts of food for the winter months (Gould and Gould 1995, p. 24). Although the honeybee brain contains slightly less than 1 million neurons, the integration of brains among the roughly 60,000 individuals in a temperate zone colony (or among the roughly 10,000 bees in a swarm) creates a more powerful “cognitive entity” (Seeley 2010, pp. 198–217).

Experimental research has shown that foraging honeybees create cognitive maps of the landscape based on several sources of sensory input (e.g., polarized light, magnetic fields). The location of a resource is communicated from the brain of one honeybee to others by means of body movements (waggle dance), vibratory sound, and odor (von Frisch 1993; Gould and Gould 1995, pp. 51–67). Thomas Seeley observed that

... the basic plan of honeybee foraging involves the colony as an “information center,” monitoring a vast area around the nest for food sources, pooling the reconnaissance of the foragers, and somehow using this information to focus a colony’s forager force on a few, high-quality patches within its foraging range (1985, p. 92).

The waggle dance communicates information in the form of a mental representation (i.e., possesses a complex hierarchical structure), and it exhibits two characteristics of modern human

language: (1) it is used to refer to subjects removed in space and time from the immediate present; and (2) it employs arbitrary conventions (Gould and Gould 1995, pp. 59–60). Among different species of *Apis*, and among different races of *A. mellifera*, multiple “dialects” of the dance language are recognized (Gould and Gould 1995, pp. 119–123). And, as noted earlier, honeybees also communicate information on the location and characteristics of potential nest sites (Seeley 2010). I have classified the honeybee super-brain as “Type I.”

Modern humans (*Homo sapiens*) possess the most highly integrated super-brain—which I have termed a “Type II” super-brain—known among the metazoans. Like the honeybee, modern humans can transmit complex, hierarchically organized, mental representations from one brain to another, although humans obviously transmit a vastly wider array of information. The modern human super-brain is integrated primarily through *syntactic language* and recent trends in the study of language (i.e., the “Minimalist Program”) that emphasize the relationship between language and “the systems that are internal to the mind” (Chomsky 1995; 2002, pp. 106–109) seem to cast it in the same light—i.e., as a system that integrates one individual brain with others. In some ways, language replicates the synaptic pathways of one brain among multiple brains (Hoffecker 2011, p. 16).

Language may represent the best evidence for the human super-brain as an organizational level above that of the individual brain (see Maynard Smith and Szathmáry 1995, pp. 282–283). Language transcends the individual brain in biological space (i.e., individual organism) and time (i.e., individual lifespan), and there is evidence that an isolated child is unable to develop a language on his or her own (e.g., Rymer 1994); in other words, a language can only exist in a social context (although a “dead” language can be reconstructed from written records). Some

suggest that language should be conceived as an interdependent entity that has co-evolved with humans like a virus (Deacon 1997).

Visual art is another means of integration of the modern human super-brain. Through painting, drawing, sculpture, and other art forms, individuals project artificial or semantic visual representations in two or three dimensions to other brains. Although the relative significance of visual art as a means of integration has declined in modern industrial societies—dwarfed by electronic media and other forms of mass communication—its importance in earlier ages probably was considerable. Other means of super-brain integration include ritual practices, body ornamentation and clothing, music, dance, cuisine, and organization of domestic space (i.e., cultural “traits” or norms). The “super-brain” represents a potential alternative to the traditional *culture concept* in anthropology.

The information gathering, storing, and sharing capabilities of the modern human super-brain permit cooperative foraging among a group in a manner analogous to that of the super-organisms. Honeybee colonies provide the closest analogue, because they also gather and share information in complex, hierarchically-organized, form. And both honeybees and modern humans make collective decisions with shared information. Ethnographic and ethnohistoric data reveal that recent hunter-gatherer societies were heavily dependent on the collective gathering, sharing, and processing of information regarding the location and characteristics of resources and “nest sites” (see Mithen 1990, pp. 52–88 with references; Kelly 1995, pp. 97–98). Richard Gould (1969, pp. 6–7) described a typical morning discussion among foragers in the Australian desert:

The men have decided to hunt emus, so the discussion centers around what the women will do. Nyurapaya has decided that her bark sandals are worn out and need to be replaced. . . Sandals are made from the green bark of *taliwanti*, a plant which grows in the sandhills. . . Should they take a chance that they will come across some edible seeds or fruit on the way to the taliwanti-place? . . . As usual, it is Katapi who solves the

problem and makes the decision. She remembers a sandy flat beyond the taliwanti-place where she thinks they may find some ripe *ngaru* . . . Her opinion is that the other women should proceed to the taliwanti place while she goes ahead to look for *ngaru*. If she is successful, she will send up a smoke signal . . .

Moreover, just as the nests of honeybees and ant colonies reflect cooperative labor, much of the technology and engineering of human societies is the product of collective thinking (e.g., Wallace 1982).

The modern human super-brain also exhibits special properties not found in the brains or super-brains of other species. Human cognitive faculties include the capacity to creatively recombine the symbols of language into a potentially infinite variety of expressions within the hierarchical structure of sentences and larger units of meaning. This has been characterized as “discrete infinity” by Noam Chomsky (1988, pp. 169–170) (see also Hauser et al. 2002). The same principle (sometimes referred to as “recursion” [e.g., Corballis 2003]) may be extended to other modes of expression (both discrete or digital and analogical) including music, dance, visual art, technology, and more (Corballis 2003; Hoffecker 2007). While *generativity* is widely assumed to be an attribute of the individual brain—especially that of an exceptional or highly creative individual—it also is a collective enterprise.

Several lines of evidence suggest that the special properties of the human brain or super-brain arose relatively late in human evolution, and that during the Lower—and perhaps much of the Middle—Paleolithic, humans lacked the creative abilities of recent and living people. The archaeological record for the Lower Paleolithic (and much of the Middle Paleolithic or African Middle Stone Age) exhibits little evidence for innovation or creativity (e.g., Schick and Toth 1993, pp. 227–284). Traces of visual art and many other media of creative expression are almost completely absent (see Klein 2009, pp. 407–410). Nevertheless, evidence of the sharing of mental representations in the form of chipped stone objects based on a mental template (i.e.,

bifaces) is present. Taken together, these patterns in the archaeological record suggest that humans once possessed a simpler form of super-brain that was perhaps more similar to that of the eusocial animals or even the non-eusocial species that evolved some degree of brain integration among members of a group (i.e., Type I or Type 0 super-brain).

The Evolutionary Ecology of the Super-Brain

Evolutionary biologists recognize multiple levels of organization and selection among life forms (Maynard Smith and Szathmáry 1995, pp. 3–14; Hölldobler and Wilson 2009, pp. 7–10). A new level emerges when its components can no longer replicate themselves except as part of a larger entity. Thus, for example, eukaryotes (true cells) are thought to have evolved from cooperating prokaryotes, while multi-cellular organisms represent a level that evolved from unicellular organisms. The super-organism is the highest widely recognized level of organization and selection in the organic world (although Maynard Smith and Szathmáry [1995, pp. 282–283] suggested that the emergence of human language exhibits some parallels with an organizational transition in biology).

Among eusocial animals, the super-brain does not represent a separate level of organization, but rather seems to function as a component of a super-organism. Thus, the evolution of the super-brain among honeybees, ants, and other super-organisms is addressed as part of the problem of the evolution of eusociality in these taxa. The problem was recognized in the original edition of *On the Origin of Species* by Darwin, who acknowledged that the existence of non-reproductive castes among the social insects presented a challenge to the natural selection model; here, he noted, “selection may be applied to the family” (1859, p. 237). The concept was eventually formulated in genetic terms (*inclusive fitness*): cooperative behavior, including

reproductive suppression, will evolve among close relatives when it increases the frequency of shared genes in the population—in this case among sibling workers (Hamilton 1964; Maynard Smith 1964).

While selection at the family level (or “kin selection”) explains how eusociality could evolve, it does not explain *why* it evolved in the various taxa described above. For the most part, it appears that super-organisms evolved because of the benefits of cooperative foraging in their respective ecological niches. To maximize the probability of finding randomly distributed tubers underground, African mole-rats tunnel individually—sampling collectively as much area as possible—and alert other colony members when a clump of tubers is encountered (Bennett and Faulkes 2000, pp. 53–85). The leafcutter ants have optimized the efficiency of their foraging (and fungus cultivation) by evolving an array of specialized worker castes, each of which performs a particular function (similar to assembly-line factory workers) (Hölldobler and Wilson 2011, pp. 51–75). The most impressive are the honeybees, whose aerial foraging pattern precludes chemical odor trails; they have evolved a sophisticated system of mapping resources and communicating the maps (and other complex information) from one brain to others—especially important in their adaptation to seasonally variable resources of the temperate zone (Seeley 1985, 1995, 2010).

Humans never evolved into a super-organism and their route to the development of an integrated super-brain was not a product of kin selection. Human societies do not meet the criteria of a super-organism. There are no “non-reproductive castes” among hunter-gatherer societies and while some complex societies contain non-reproductive individuals or groups (usually associated with religious orders), these constitute a small proportion of the whole society. Moreover, the degree of genetic relatedness appears too low to account for cooperative

behavior among most individuals (i.e., outside parent-offspring or sibling relationships). This is readily apparent in large complex societies, but also seems to be the case in small hunter-gatherer societies (see Hill et al. 2011).

The parallels between eusocial insect societies and complex human societies are superficial; the former are simply very large nuclear families (primarily a mother and her non-reproducing daughters). They are the product of an evolved system of mass reproduction that permits a single individual (queen) to give birth to hundreds or thousands of offspring, creating a kin-selected society on the scale of a modern human city-state or small nation. While the fast-breeding mole-rats are capable of generating at least a small society in the same way, humans are severely constrained by their reproductive biology—slow gestation time, small litter size, protracted infant dependency—and limited to a few offspring (especially in a hunter-gatherer setting). Complex human societies have replicated the specialized worker castes of the eusocial insects through a different evolutionary path.

Humans apparently developed cooperative social networks through the evolution of reciprocal relationships among individuals outside the immediate family. *Reciprocity* has long been suspected as a major factor in human sociality (e.g., Trivers 1971; Wilson 1975, pp. 553–553; Maynard Smith 1982, pp. 167–173). It seems to have permitted early humans to break out of a social pattern inherited from the African apes that probably was similar to that of living chimpanzees (*Pan* sp.), some of whom inhabit open woodland/savanna margin, forage over wide areas, consume a highly varied diet of plant and animal foods, make tools, and sometimes hunt cooperatively (Goodall 1986; McGrew 2004). Their societies are composed of adult males and females that mate promiscuously, and do not form long-term pair bonds. The females move to other groups while the males remain in the same group (and attack males from other groups)

(Layton and O'Hara 2010). Early humans may have initially developed reciprocal relationships through long-term pair-bonding between males and females (Chapais 2008). In any case, they eventually produced a radically different form of social organization in which the coefficient of relatedness among band members was comparatively low, while separate foraging bands were linked by wider cooperative networks (Hill et al. 2011).

I suggest that the driving force behind the development of reciprocal relationships and wider social networks in early humans was probably the same factor that promoted the evolution of eusociality—the benefits of *cooperative foraging*. More specifically, I suggest that early humans were confronted with the problem of locating and acquiring a variety of widely dispersed resources, and that this problem was most effectively solved with a foraging strategy similar to that of the eusocial animals, i.e., resource locations are identified by one or more foragers who communicate the information to others (or an “information center” foraging strategy [Seeley 1985]). The model assumes central place foraging and relatively large average patch size (in order to accommodate multiple foragers).

The human family unit by itself probably was too small to implement an information-center foraging strategy over a large area containing a wide variety of resources, and, as in the case of the honeybee colony, odor trails and vocal signals would have been insufficient. Early humans presumably had to develop the means of communicating complex information on the location and characteristics of the resource in a manner analogous to the waggle dance (i.e., employing arbitrary conventions and making reference to subjects outside the immediate spatial/temporal setting). Because increases in family size were constrained by human reproductive biology, early humans were compelled to develop and maintain cooperative networks through balanced reciprocity among non-relatives. And although recent hunter-

gatherers maintain alliances through a variety of reciprocal acts, including gift-giving and food-sharing (Layton and O'Hara 2010, pp. 96–105), information exchange is especially important (Mithen 1990, pp. 52–88; Kelly 1995, pp. 97–98).

The Greater Apes in general, and chimpanzees in particular, seem a logical source for the evolution of reciprocal alliances based on the currency of information pertaining to resource locations. Chimpanzees exhibit some integration of brains (“Type 0” super-brain) in a non-eusocial context, and they possess a rich repertoire of vocalizations and gestures (in addition to chemical communication) (Call and Tomasello 2007). The communication of mental representations analogous to those of the honeybee waggle dance might have been through the medium of vocalization or gestures or both (presumably not pheromones). Among eusocial animals, communication is invariably multimodal (Gould and Gould 1995; Hölldobler and Wilson 2009).

The available data from early human fossils and archaeological sites are not sufficient to reconstruct diet and foraging patterns in detail (e.g., Stern 1994; Wood and Strait 2004; Ungar et al. 2006, pp. 213–219), although, in general, they accommodate the emergence of an information-center foraging strategy proposed here roughly 2.0 million years ago. After 2.5 million years ago, C₄ grasslands expanded in East Africa (Cerling 1994), and by 2.0 million years ago, archaeological sites can be identified in this setting (Plummer et al. 2009). This may reflect a shift to habitat with more widely dispersed resources. Even in tropical environments, where biological productivity is high, modern humans live at low population densities, and forage over very large areas, compared to chimpanzees (Layton and O'Hara 2010, p. 91, table 5.3). Several lines of evidence point to a diverse diet at ~2.0 million years ago, which is thought to have included

plant resources such as berries, fruits, nuts, leaves, pith, flowers, shoots, seeds, and gum, as well as underground resources such as roots, tubers, corms and rhizomes . . . supplemented by animal resources such as insects, eggs, small reptiles (e.g., lizards, tortoises, and snakes), amphibians, mollusks, and fish, as well as larger animals (Schick and Toth 2006, p. 31).

This suggests a complex mosaic of food resources and patch types—at least some which are potentially large patches—distributed across the landscape, along with mobile prey animals.

Other essential resources include specific types of stone for artifact manufacture. It is not clear, however, if the archaeological sites represent central place foraging (e.g., Kroll 1994).

In any case, the archaeological record indicates that humans were externalizing (and thus sharing) mental representations in the form of chipped stone artifacts that exhibit a design or “mental template” by 1.7 million years ago (e.g., Schick and Toth 1993; Wynn 1995; Mithen 1996; Pelegrin 2009). These artifacts provide empirical support for the existence of a super-brain at this time—at least one reflecting a “Type I” level of integration. They are analogous to the waggle dance because they are mental representations projected outside the individual brain that communicate a relatively complex and structured body of non-genetic information to one or more other brains. The appearance of these externalized mental representations reflects an evolved neuro-motor function unique to *Homo* and an indirect consequence of hominin bipedalism: the use of paired hands for transforming natural objects in accordance with structures of non-genetic information stored in the brain (Greenfield 1991; Napier 1993; Mountcastle 2005). The human vocal tract subsequently acquired an analogous function (Hoffecker 2007, 2011).

I further suggest that the subsequent emergence of the modern human mind or the “Type II” super-brain represents the evolution of a more highly integrated super-brain derived from the super-brain of early humans. I suggest that it was a consequence of the dynamic evolutionary setting created by a super-brain based on reciprocal networks rather than genetic relatedness or

kin selection. Such relationships are inherently unstable because selection will favor subtle cheaters and crafty deceivers who pursue selfish goals (or the goals of very close relatives) over the interests of the society as a whole. They may promote the evolution of “Machiavellian intelligence” (e.g., Byrne and Whiten 1988), and the growth in brain volume during later human evolution has been attributed to selection for increased social skills (“social brain hypothesis” [Dunbar 1996, 1998] see also Holloway 1967). Modern human social patterns suggest that significant advantages would have accrued to individuals who built wider and stronger networks. If the networks were based on information sharing, their expansion and intensification would have been fueled with increased quantities of information. At the same time, greater gathering of environmental data probably enhanced foraging success.

The honeybee colony represents an evolutionary context for humans as important as that of the primates. While the cooperative foraging of the eusocial animals in general provides insights to early human ecology, the information sharing strategy of the honeybee is a unique analogue for early human organization. Humans are the only other known metazoan that evolved a similar dependence on the sharing of information in complex hierarchically-organized form. But in contrast to the stable kin-selected adaptation of the honeybee (probably unable to evolve a significantly expanded brain anyway, due to functional-anatomical constraints), humans developed their information-center strategy on the unstable basis of reciprocal networks that probably favored constant growth in both social skills and information storage.

Judging by the standards of recent hunter-gatherers, the quantity of information collected and stored eventually became immense (Mithen 1990). Because the information had to be transmitted to another spatial/temporal context, the received sensory input (primarily visual) concerning plants, animals, and other resources, had to be converted to symbols, and because the

information was communicated from one brain to another, the symbols had to be fixed by convention (Bickerton 1990). The sheer volume of information must have required organization, such as systems of categorization and hierarchical classification. The syntactical language that humans subsequently developed functions as both a system of thought (or “information processing”) and means of internal communication or super-brain integration (Chomsky 1995).

The modern human mind or the Type II super-brain emerged when humans evolved the ability to recombine non-genetic information into a potentially infinite variety of novel arrangements or structures (i.e., “generativity”). Because this is considered the “core property” of language (Chomsky 1988, 2002; Hauser et al. 2002), it suggests that the advent of syntactic language is coincident with the modern human mind. As noted above, however, the modern human ability to creatively recombine information extends to other media, including visual art, dance, music, cuisine, domestic space, and more (Corballis 2003, 2011; Hoffecker 2007, 2011). This ability had a significant impact on human ecology, because humans had already begun to apply mental representations to technology. With the emergence of the Type II super-brain, humans began to creatively recombine the elements of technology to produce innovative and increasingly complex forms—this trend eventually had major consequences for diet, economy, and population density. Perhaps this was the point at which later humans achieved a stable evolutionary strategy; anatomical changes, including increases in brain volume, ceased and the subsequent “evolution” of modern humans was primarily confined to non-genetic information.

The Archaeology of the Super-Brain

The archaeological record contains much pertaining to the integration of brains within human groups. It includes archaeological data related to human ecology and foraging strategy that

provide an essential context for the emergence of a super-brain. It also includes artifacts and features that may be considered “concrete embodiments of thoughts” (Childe 1956, p. 1). By 1.6 million years ago, some humans were making artifacts that were analogous to the waggle dance of the honeybee (i.e., chipped stone objects shaped in accordance with a hierarchically structured design). These artifacts, along with much of the younger archaeological record, offer evidence for the sharing of mental representations among individuals or integration of brains. Fossil anatomical evidence for changes in cranial morphology, including brain volume, also contributes an essential context (e.g., Tobias 1971; Holloway 1995; Holloway et al. 2009).

Lower Paleolithic

The earliest known artifacts do not reflect the imposition of a mental template on a piece of stone (i.e., they do not represent a “type” in the mind of their maker), but rather appear confined to the reduction of natural objects (Toth 1985; Schick and Toth 1993, 2006). The cores, choppers, scrapers, and other artifacts of the *Oldowan Industrial Complex* (≤ 2.6 million years ago) are similar in form to the cobbles and rock fragments from which they were chipped (Toth 1985, p. 107, Fig. 5). This conclusion extends to rounded objects or “spheroids,” which can be reproduced by repeated battering of a cobble in the capacity of a hammerstone (Schick and Toth 1993, pp. 130–133).

The significance of the Oldowan artifacts for the emergence of a super-brain lies in their implications for human ecology. The appearance of hominin sites containing stone artifacts ~2.6 million years ago is one of several lines of evidence that suggest a major shift in diet and foraging strategy (e.g., Ungar et al. 2006). The stone tools, which are beyond the capacity of living apes (Toth et al. 2006), indicate new types of food and/or new means of obtaining and

processing foods, which may have included digging tubers and other “underground storage organs” (Laden and Wrangham 2005) and/or stripping meat off large mammal bones (e.g., Pickering and Domínguez-Rodrigo 2006). Supporting evidence may be found in the analysis of human bone chemistry (e.g., Sillen et al. 1995; van der Merwe et al. 2008) and animal bones associated with the artifacts (e.g., Bunn and Kroll 1986).

Perhaps the most striking indication of a shift in dietary niche and foraging tactics is the massive expansion in geographic range undertaken at least 1.8 million years ago by humans who were similar in anatomy and tools to the makers of the Oldowan. This expansion saw the invasion of new environments that were cooler, less productive, and more seasonal than those occupied by the australopithecines (e.g., Gamble 1994, pp. 117–143; Hoffecker 2005a). In many ways, it parallels the colonization of the temperate zone by honeybees (e.g., Gould and Gould 1995, p. 24). Finally, fossil crania indicate a “major increase, rapid, both allometric and non-allometric” in brain volume 2.5–1.8 million years ago (Holloway et al. 2009, p. 1331, Table 2).

The significant changes in human foraging patterns at this time may indicate that the development of the “information center” strategy hypothesized above took place before the appearance of any archaeological traces of the sharing of mental representations (i.e., bifaces of chipped stone). Presumably, any communication of complex, hierarchically organized information pertaining to foraging was performed with vocal and/or gestural means (or possibly with perishable materials lacking archaeological visibility). This would explain why humans who inhabited East Asia from at least 1.6 million years ago until the arrival of modern humans apparently pursued a foraging strategy similar to that of their African and west Eurasian contemporaries (and also exhibited later cranial expansion) but rarely produced bifaces (e.g., Boaz and Ciochon 2004).

The bifaces that appear roughly 1.76 million years ago in Africa (Lepre et al. 2011) may simply reflect a novel medium of expression for a phenomenon already established throughout *Homo* populations. They remain important, nevertheless, as evidence for an integrated super-brain—at least at the level of the honeybee (“Type I”) if not higher. The large stone bifaces of the *Acheulean Industrial Complex* are the oldest known external mental representations—they reflect the imposition of a design or mental template on a piece of rock (like the phenotype of an “organism” based on non-genetic information) (Gowlett 1984; Clark 1994; Mithen 1996, pp. 117–119; Pelegrin 2009, pp. 100–102) (but see Noble and Davidson [1996, p. 200] for an alternative view). Both their formal structure and pattern of spatial-temporal variation have been addressed (e.g., Isaac 1977; Wynn 1995; Gowlett 2006). Acheulean bifaces exhibit an analogical ovate form in three dimensions, but they were produced through a digital process of discrete flake removals. Except when they were flaked directly from a nodule or cobble, their production entailed two irreversible hierarchical levels: (1) striking a large flake blank off a core, and (2) flaking both sides of the blank to create the ovate form (e.g., Schick and Toth 1993, pp. 237 – 245).

Although the more refined bifaces of the later Acheulean reflect an added level in the form of edge trimming (e.g., Schick and Toth 1993, p. 263), archaeologists have often noted the lack of change in the basic design of the biface for more than a million years. As Thomas Wynn remarked, “it would be difficult to overemphasize just how strange the handaxe is when compared to the products of modern culture” (1995, p. 21). The pattern suggests the absence of the creative recombination of elements characteristic of the products of the modern human mind, suggesting that the early *Homo* super-brain was similar to that of the honeybee colony, i.e., capable of gathering and transmitting information, but not generating novel structures.

Nevertheless, variations in biface form tend to cluster in space and time (see Isaac 1977, pp. 116–145; McPherron 2006, pp. 267–285) perhaps reflecting local “dialects” analogous to those of the honeybee dance (see Gould and Gould 1995, pp. 119–123).

The most important development in human evolution between 1.5 and 0.5 million years ago seems to be significant growth in cranial volume (e.g., Rightmire 1990, pp. 230–233; Holloway 1995, pp. 108–113). By 0.5 million years ago, humans in Africa and Eurasia had evolved a brain that falls within the lower range of modern humans. Other than the refinement of bifaces described above, however, there is little archaeological evidence for changes in technology, diet and foraging, or other aspects of behavior during this rather protracted interval (e.g., Klein 2009). The increases in brain size might reflect the steady growth in the volume of information collected, processed, and shared in the dynamic social setting of early human groups and networks (see Dunbar 1996), which could explain why similar increases took place among different species of *Homo* (i.e., local environmental setting was a lesser factor).

Middle Paleolithic/Middle Stone Age

After 0.5 million years ago, there are changes in the archaeological record that reflect a capacity for organizing larger quantities and varieties of information. The information, which is expressed in the form of core, tool, and weapon design, manifests a more complex hierarchical structure with many levels and varied components. The earliest is the appearance of prepared core technology, later followed by evidence for production of composite tools and weapons. There also is a pattern of increasing regional artifact variability in Africa that mimics the pattern of local cultural variation so evident in the archaeological record of modern humans.

These developments seem implicated in the subsequent emergence of the modern human mind (or “behavioral modernity”) (McBrearty and Brooks 2000, pp. 494–500; Ambrose 2001, pp. 1751–1752, 2010; Pelegriin 2009, pp. 102–107) and the Type II super-brain. The implicit assumption is that an increased capacity for organizing information in the realm of technology reflects a similar capacity in other spheres that lack archaeological visibility. Just as it is assumed that Lower Paleolithic bifaces reflect an ability to externalize mental representations through vocal and/or gestural media, it is assumed that Middle Paleolithic/Middle Stone Age sequences of core reduction and implement composition are paralleled by comparable information-processing capabilities in other areas (see, for example, Leroi-Gourhan 1964, 1965; Deetz 1967; Holloway 1969; Haidle 2009; Ambrose 2010).

The basis of such an assumption seems to have been strengthened by brain-imaging research that reveals what Greenfield (1991, p. 531) termed “a common neural substrate” for various information-processing functions (Goldberg 2009; Stout 2010). For example, Positron Emission Tomography (PET) scans indicate activation of left mesial temporal cortex and left inferior frontal gyrus for both spoken and sign (manual) language (Emmorey et al. 2007).

In its developed form, prepared (or *Levallois*) core technology comprises a set of procedures for generating flakes or blades of specific size and shape from large pieces of stone (e.g., Schlanger 1996). Technological analysis indicates that several steps are involved: (1) acquisition of a piece of stone of sufficient size and quality; (2) preparation of a continuous surface (or series of “striking platforms”) extending around the perimeter of the stone; (3) shaping of the upper surface of the core by striking a series of horizontal blows around the perimeter; (4) at this point, the tool-maker may choose from a variety of strategies for generating flakes or blades from the upper surface (see Boëda 1995, pp. 41–68). Describing the relationship

between the upper surface of the core and the platform surfaces around the perimeter, Boëda (1995, p. 46) notes that:

the two surfaces are hierarchically related: one produces defined and varied blanks that are predetermined, and the other is conceived of as a surface of striking platforms for the production of predetermined blanks. In the course of a single production sequence of predetermined blanks, the role of the two planes cannot be reversed.

Boëda also notes the collective character of prepared-core methods shared among members of a group and “transmitted from generation to generation” (1995, p. 53). Over great distances of space and time, these groups devised non-random variations on prepared-core flaking strategies.

Composite tools and weapons can be reconstructed from traces of microscopic wear and adhesives on the stone blanks that were inserted into handles and shafts. The microwear is characteristic of stone blades and points set into wooden handles or shafts. In some cases, it indicates the use of a binding cord or thong. Microscopic traces of adhesives have been found on the stone blades and points in both African and Eurasian sites and include resin, bitumen, and ochre (e.g., Anderson-Gerfaud 1990; Boëda et al. 1996; Lombard 2005, 2007). Recent analysis of impact scars on blades from several South African sites indicates that they were attached in two different ways—on the end and on the side of a wooden shaft (Villa et al. 2010).

The implications for human cognition are considerable, especially if the complex prepared-core technology described above is incorporated into the production process as one of several sub-assembly units (or “techno-units” [see Oswalt 1976, pp. 38–44]) that nests within a larger hierarchically-organized structure (Ambrose 2001; Hoffecker 2007, pp. 371–373; Barham 2010, pp. 374–378). The other techno-units require shaping and grooving of a wooden handle or shaft, and preparation and application of the binding agent(s). Each component sub-assembly involves obtaining and processing a different type of material. The components are brought together in a preconceived design that exhibits at least a few alternative forms, e.g., stone-tipped

spear versus hafted cutting tool or side-blade versus end-blade, and the parallels with language were noted by Ambrose (2001, p. 1751):

Conjunctive technologies are hierarchical and involve nonrepetitive fine hand motor control to fit components to each other. Assembling techno-units in different configurations produces functionally different tools. This is formally analogous to grammatical language, because hierarchical assemblies of sounds produce meaningful phrases and sentences and changing word order changes meaning.

Another pattern in the archaeological record that anticipates later trends associated with behaviorally modern humans is the emergence of regional styles in the design of stone artifacts—especially small bifacial forms and points—throughout Africa. Thus for example, Middle Stone Age (MSA) sites in North Africa yield distinctive stemmed points, while sites in west-central Africa contain equally distinctive narrow elongated bifacial points (see Clark 1993, p. 155; McBrearty and Brooks 2000, pp. 497–500). By 250,000 years ago, the African record acquires a rather “modern” look that is quite unlike the pattern of variation in the Lower Paleolithic. This would seem to reflect an increased sharing of information and greater degree of integration among brains within local groups.

Behavioral modernity is widely recognized in the archaeological record on the basis of preserved material traces of symbolism (or “symbolic storage in material form”) (e.g., Donald 1991; Wadley 2001; Henshilwood and Marean 2003). Archaeological evidence of symbolism, such as abstract design or figurative art, is widely viewed in turn as a proxy for fully modern or syntactic language, although some suspect that language appeared much earlier than the oldest known traces of symbolism (e.g., McBrearty and Brooks 2000, p. 486). Alternatively, modernity or the modern mind may be equated with the property of *generativity*—the capacity for creating a potentially infinite variety of information-based structures comprising multiple hierarchical levels (Corballis 2003; Hoffecker 2007, pp. 375–376), which in turn I attributed to the emergence of the fully integrated or Type II super-brain (Hoffecker 2011). The externalized

“structures” range across all media both symbolic and non-symbolic, and the evidence thus embraces virtually all categories of archaeological data. In this alternative context, the significance of the symbols—as a proxy for syntactic language—lies in both their role as an expression of generativity and as the primary means of super-brain integration.

The how, when, and where of the transition to modernity also remains a subject of debate, and the answers seem likely to shift as new archaeological evidence becomes available. Most archaeologists recognize the trends in the Middle Paleolithic/African MSA that anticipate modernity described above, but some suggest that a triggering event such as a genetic mutation related to working memory capacity or speech was necessary for the final transition (e.g., Coolidge and Wynn 2005; Wynn and Coolidge 2010; Klein 2009, pp. 647–649). If modernity is equated with generativity, brain-imaging research suggests that expansion of the prefrontal cortex, which is the center of integration and novel task performance (Raichle et al. 1994; Goldberg 2009, pp. 89–92), as well as working memory (Goldberg 2009, pp. 92–98), might have been critical (see Holloway 2002).

More generally, the over-sized cranium of late Middle Pleistocene *Homo* may indicate that the volume of information stored and processed in the individual brain had reached a threshold or a crisis point. Language would have alleviated “information overload” (see Gleick 2011) by providing a means of organizing it more efficiently. The extensive, hierarchically structured, classificatory systems of plants, animals, and other natural phenomena maintained by all recent hunter-gatherer societies could exist only in the context of a language.

As for dating the transition, most archaeologists cite the age of the pieces of ochre exhibiting abstract designs—along with shell ornaments and some new technologies—of ~75,000 years ago from Blombos Cave (South Africa) (Henshilwood 2007). The recent dating

of perforated shell ornaments—which may have been symbols of the social groups that wore them—in North Africa and the Levant roughly 135,000 years ago (Vanhaeran et al. 2006) may indicate that the transition is significantly earlier. In any case, it seems unlikely that the transition occurred over a broad area and among more than one local population. More probably, the final leap to modernity occurred among one group of *Homo sapiens* in sub-Saharan Africa, and both genetic and linguistic evidence point towards southern Africa (e.g., Atkinson 2011). If “information overload” was a factor, a rich tropical environment—where biodiversity is high—is a logical setting, especially in contrast to the drier and colder environments of northern Eurasia (e.g., Whittaker 1975).

Upper Paleolithic/Later Stone Age

The period between ~50,000 and 12,000 years ago is classified as the *Upper Paleolithic* (or African Later Stone Age [LSA]), following the terminology of the 19th century, but the classification no longer seems appropriate. It was a critical phase in human history, during which anatomically and behaviorally modern humans dispersed out of Africa and rapidly throughout southern and northern Eurasia and Australia. They adapted to an extraordinary range of habitats and climate zones with the creative powers of the modern collective mind or Type II super-brain, generating new and often complex technologies to redesign themselves as organisms with tailored clothing, watercraft, small-game traps, artificial memory systems, and many other implements and devices (e.g., Hoffecker 2005b; Klein 2009, pp. 672–683). Like language, the super-brain differentiated itself into numerous regional nodes or “archaeological cultures” that acquired a distinctive local character in the later Upper Paleolithic and especially the post-Paleolithic.

The Upper Paleolithic archaeological record provides most of the evidence for symbolism and inferred language abilities before the postglacial epoch, because the scarcity of African MSA data on symbolism. More importantly from the perspective adopted here, it provides virtually all of the evidence for generativity in this time range. The capacity for creating a potentially infinite variety of structure in all media that possess some archaeological visibility can be documented only with a wide range of material remains in space and time (Hoffecker 2007, pp. 361–362). In fact, the potential for infinite creation cannot be confirmed, but it is implicit in the many hierarchical levels and the variety of elements that may be identified in Upper Paleolithic paintings, sculptures, and engravings, as well as house floors, bone tools, and other forms of technology.

The archaeological record of the Upper Paleolithic also provides an illustration—the earliest adequate illustration—of how the super-brain accumulated knowledge over many generations, and how this accumulated knowledge led to increased settlement size and, probably, higher population density. A significant increase in the size of settlements—at least short-term settlements—is apparent in parts of northern Eurasia after 30,000 years ago. They include the *Gravettian* feature-complexes at places such as Dolni Vestonice (Moravia) and Kostenki (Russia); the latter exhibits a linear arrangement of hearths surrounded by large pits, and may have been occupied by more than 50 people at one time (Svoboda et al. 1996, pp. 145–170; Amirkhanov 1998). These sites exhibit a size and complexity without precedent in human evolution, and their appearance presumably reflects the cumulative impact of various innovative technologies (e.g., nets, throwing darts, cold storage, snares, fishing gear) that increased the number of persons that could be supported per unit area (Hoffecker 2011, pp. 121–128). Stable

isotope analyses of human bone indicate a more eclectic diet, including freshwater aquatic foods, during this interval (Richards et al. 2001).

In the millennia that followed the cold peak of the Last Glacial Maximum, Upper Paleolithic groups in various parts of the world began to anticipate the sedentary settlements of the postglacial epoch, constructing groups of houses, sometimes with paved floors (e.g., Hoffecker 2011, pp. 133–137). Technological innovations of the period include pottery vessels (East Asia), which suggest a less mobile residential pattern (e.g., Boaretto et al. 2009). Although the emergence of farming villages is attributed primarily to climate change at the end of the Pleistocene, the collectively accumulated technical knowledge of the later Upper Paleolithic was a more significant factor (Bellwood 2005; Hoffecker 2005b).

Neolithic and Ancient Civilization

During the early postglacial epoch, the density of human populations in some areas began to grow exponentially. In the Near East, and somewhat later in China and other regions, Neolithic farming villages expanded into towns and urban centers, yielding communities composed of thousands or tens of thousands of individuals (e.g., Adams 1981; Chang 1986; Maisels 1999, p. 175; Coe 2005). The exponential growth of populations and communities invariably yielded social and economic hierarchies containing various categories of technical specialists (potters, scribes, metallurgists, etc.). It also yielded a hierarchical reorganization of the modern human super-brain: the processing and storage of information in complex societies is both specialized and hierarchically structured. Individuals (administrators, generals) and groups (e.g., priests, scribes) organized information, drew conclusions or made decisions, and generated

representations—edicts, monuments, calendars, etc—that were shared with many others as a blueprint for thought and action.

More than the high-tech foragers of the Upper Paleolithic, civilization illustrated how modern humans had achieved a level of organization higher than that of the individual organism, but without a genetically constructed super-organism (cf. Maynard Smith and Szathmáry 1995, pp. 281–309). The balanced reciprocity and alliance networks of hunter-gatherer societies were replaced, however, with even more unstable hierarchical relationships and extreme contrasts in wealth and social status. The ancient civilizations faced a constant threat of internal violence and collapse (e.g., Assmann 2002).

Explaining the origin of complex society and civilization remains a challenge; the process may have varied from place to place (e.g., Kemp 1989; Coe 2005; Algaze 2008). The reason for the reorganization of the super-brain is readily apparent, however, and probably applies to all complex societies. The small societies of recent foraging peoples, as well as those of small communities within larger societies, are composed of individuals whose brains are integrated into one super-brain (i.e., each person shares mental representations with everyone else). The exponential growth of community size during the postglacial epoch in the context of simple communications technology rendered this impossible (Kosse 2001). Thousands of brains can be integrated only within a hierarchical structure comprising multiple (although interconnected) super-brains in the form of sub-groups and institutions; the threshold appears to be roughly 25,000 individuals (S. Lekson, pers. comm., 2011).

The early civilizations invested heavily in novel information technologies, because it is impossible to manage very complex social and economic organizations without written records and systems of weights and measures (e.g., Algaze 2008). This was a significant externalization

of brain function, because the externalized representations were not merely stored outside individual brains (memory function), but also were recursively or creatively manipulated in this setting (generative or semantic function). The latter is an interactive process between external and internal representations.

Although the mental hierarchy of the ancient civilizations is illustrated by written records, archaeological data are necessary to establish its initial appearance. The distribution of artifacts and features in the early phases of civilization in the Near East, China, Mesoamerica, and elsewhere illustrates extreme social stratification through contrasts in the dwellings, tombs, and their contents; the hierarchical restructuring of the super-brain may be inferred from this pattern (e.g., Chang 1986; Maisels 1999; Coe 2005). Archaeological evidence for organized warfare and military structures in the early civilizations also probably indicates stratified thinking. More direct evidence may lie in phenomena like calendars or ritual liturgies—invariably created by a few individuals and then adopted by other members of the society. The rise of technical specialists produced a parallel hierarchy of mind, because potters, metallurgists, and other artisans were applying their knowledge to the creation of complex external representations that were distributed to others.

Summary and Conclusions

Much of what makes humans unique among living organisms is tied to their gathering, processing, and sharing of *information* in very large quantities. Recent hunter-gatherers were heavily dependent upon the sharing of information pertaining to resources and other features of their environment (Mithen 1990; Kelly 1995), and it seems likely that earlier humans pursued a similar foraging strategy. An “information-center” strategy (see Seeley 1985) may have initially

evolved ~2.5–2.0 million years ago in conjunction with significant changes in diet and foraging patterns, and is probably related to subsequent human expansion into the temperate zone.

The eusocial animals, which represent *super-organisms*, provide both a comparison and contrast to human societies. They evolved cooperative foraging adaptations that entail collection and sharing of information about resources and nest sites. In particular, honeybees evolved the means of communicating complex, hierarchically structured information from one individual brain to another in the form of body movements (“waggle dance”), often compared with human language (e.g., Bickerton 1990, p 153). This resulted in an integrated collective brain or *super-brain*, and the honeybee social group has been characterized as a “cognitive entity” with emergent properties (Seeley 2010, pp. 198–217). The existence of an early human super-brain probably is reflected in the archaeological record by the appearance of bifaces 1.7–1.5 million years ago. While the true significance of these objects may never be known (perhaps they were exchanged as gifts), they indicate the capacity for communicating complex, hierarchically structured information from one brain to another analogous to the honeybee waggle dance.

If early humans evolved an information-center foraging strategy and super-brain analogous to that of the honeybee, they most probably did so outside of the context of a super-organism, which is based on a high coefficient of genetic relatedness. Instead, humans must have shared information through *reciprocal relationships* among non-siblings and family units, perhaps an outgrowth of reciprocal pair-bonding of males and females (Chapais 2008; Hill et al. 2011). This allowed integration of brains and formation of social networks far beyond the limits of close genetic relationships that underlie the cooperative foraging among the components of a super-organism. It also created a dynamic social environment in which selection would favor

subtle cheating and competitive networking, and the substantial expansion of the human brain between ~1.5 and 0.25 million years ago has been attributed to social skills (Dunbar 1996).

Regardless of the driving force behind the expansion of the later *Homo* brain, it clearly corresponds with a substantial increase in the amount of information processed and stored by each individual and shared among the members of each social group. Language provided one means of organizing much of this information, as well as more fully integrating brains within a group. The organization of information in hierarchical form with many levels and embedded components reached a threshold at which a potentially infinite variety of structures could be generated by recombination of elements and levels.

Modern humans are unique among all living organisms with respect to the vast body of collected, shared, and stored non-genetic information that pervades their lives. Because of their ability to externalize non-genetic information in various media outside the brain (evident among early humans at least on a simple level), modern humans used their capacity to recombine information on many hierarchical levels to create increasingly complex technologies that are themselves analogous to organisms because they are based on a design. The archaeological record indicates at least broad co-occurrence of symbolism and *generativity*, suggesting a link between the primary means of modern human super-brain integration (language) and the ability to create a potentially unlimited variety of structures based on information.

Human evolutionary biology reached a relatively stable equilibrium at this point, after which changes in ecology and society were almost entirely a consequence of the developing structures of non-genetic information, including those related to the integration of brains (i.e., communications and information technology).

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Table I. A Proposed Classification of Super-Brains.

TYPE	TAXA	CHARACTERISTICS	COMMENTS
TYPE 0	Examples: <i>Pan troglodytes</i> <i>Atta sp. (leafcutter ant)</i> <i>Heterocephalus glaber (naked mole-rat)</i> <i>Australopithecus sp.?</i>	Characterized by limited integration among brains within a social group: transmission of <i>signals</i> that function as sensory input from one brain to others; complex information (e.g., map) cannot be transmitted.	This is the most common form of brain integration among eusocial animals, and it also is present among various non-eusocial taxa.
TYPE I	<i>Apis mellifera</i> (honeybee) <i>Homo habilis?</i> <i>Homo ergaster?</i> <i>Homo erectus?</i>	Characterized by the transmission of mental representations comprising several hierarchical levels from one individual brain to others, but lacking creative recombination of elements.	Represented among living taxa only by the honeybee, but possibly a model for the early human super-brain.
TYPE Ia	<i>Homo heidelbergensis?</i> <i>Homo helmei?</i> <i>Homo neanderthalensis?</i>	Characterized by the transmission of mental representations comprising multiple hierarchical levels from one individual brain to others, and at least limited recombination of elements.	This is an entirely hypothetical form of super-brain, not found among any living taxa, but suggested by archaeological data.
TYPE II	<i>Homo sapiens</i> (modern humans)	Characterized by the transmission of mental representations from one individual brain to others, and by recombination of information on multiple levels with potentially infinite variations (i.e., "generativity").	Equated with the modern human mind and known only in modern humans.