



THE IMPACT
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The Landscape of Intelligence

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Astrobiology and Intelligence

The question of how intelligence evolves on different planets is a factor of fervent interest in many scientific and public domains. Yet, it has received little, if any, serious scientific attention in astrobiology. Astrobiology relies on an elegant paradigm: earth as a natural laboratory, i.e., investigate how life arose and evolved on this planet and apply that knowledge to detecting and understanding extraterrestrial life. Thus, the study of the evolution of intelligence fits squarely within the field of astrobiology. But, despite a wealth of accessible data from “mainstream” fields, astrobiology has limited itself to studying the origin and evolution of early life and has not made the connection between these basic processes and intelligence. Why, in its fifty-year history, has there been essentially no empirical work within astrobiology on intelligence?

What is intelligence?

Intelligence is, by nature, a fuzzy concept. That is, there are no strict boundaries on it and there is no scientific consensus on its definition. The study of intelligence, therefore, necessitates a strong reliance on “bottom-up” empirical description of a range of phenomena rather than a

“top-down” hunt for a precise exemplar. Intelligence is not a binary trait. Rather, it is a multidimensional phenomenon which expresses itself in varying phenotypes and levels of complexity and is interconnected with the entire psychological make-up of any animal. Nevertheless, if we wish to use a working definition of intelligence, then we can refer to intelligence as a level of cognitive complexity. i.e., how an individual acquires, processes, stores, analyzes, and acts upon information and circumstances.

Despite its complexities and fluid boundaries, the phenomenon of intelligence is amenable to empirical scientific investigation just as any other biological property. The absence of the study of intelligence from astrobiology is due to a complex set of historical and psychological roadblocks. One of these may be the mistaken assumption that intelligence is not scientifically tractable. But foremost of these is our species’ adherence to the wrong model of life on earth, one that promotes misconceptions which impede the way forward in the scientific study of intelligence in astrobiology.

The Darwinian Revolution

Charles Darwin established that all species on earth, including humans, descend from common ancestors and, along with Alfred Russell Wallace, identified the mechanism driving biological evolution – natural selection (Darwin, 1859, 1871). When the modern evolutionary synthesis emerged in the 1930s to the 1950s a consensus was reached in which natural selection was recognized as the central (but not exclusive) means by which evolution occur. Darwin's work unified the field of biology and provided a fertile and substantive foundation for studying intelligence. But, well before Darwin another model of life on earth had already taken hold of

the human mind - one that serves a strong desire to be superior to and separate from the other animals, i.e. the scala natura.

Scala Natura

The scala natura is an Aristotelean model of nature from the third century BCE (but which probably goes back much further). According to this model, nature is arranged on a linear scale of progression with inorganic objects, e.g., rocks, on the lowest rung of the scale, then plants, then up to “lower” animals (invertebrates), to vertebrates to “higher” mammals such as primates, and, finally, humans, who occupy a separate, superior position above all other animals. Humans are considered the most “advanced” life form on the planet, having a more “perfect” form than the other animals and, possessing of unique qualities (Marino, 2007). This notion is alive and well today in terms such as “higher vs lower” and “primitive versus advanced” to describe species differences. The scala natura constrains the entire process of thinking about extraterrestrial intelligence because it leads to the assumption that astrobiology has only one example of a unique intelligence on earth and, therefore, nowhere to go investigatively.

Sui generis

The scala natura leads to well-known self-perpetuating assumptions, such as *sui generis*, meaning “one of its own kind” and notions of anthropocentrism and directionality – all of which are antithetical to the astrobiology paradigm. The result has been a longstanding argument about contingency versus convergence between those who view extraterrestrial intelligence as highly improbable and those who do not. As far back as 1904, Alfred Russell Wallace expressed strong reservations about extraterrestrial intelligence on the basis that the number of steps it would take

to create an intelligence as complex as that of a human is too improbable (Crowe, 2008). And over the last several decades many leading scientists have vociferously argued that the emergence of a human-like intelligence is based on a highly improbable set of events (contingencies) which cannot be repeated elsewhere. But these interminable debates miss the point by focusing on human intelligence exclusively and leaving out consideration of the framework of all species in which humans are embedded.

From the Big Bang to the Big Brain?

Scala natura thinking is also compatible with teleological assumptions about intelligence. Teleology, the appeal to a goal-directed, purposeful progression toward an end point, seems to suggest that all life on Earth has been moving toward the eventual emergence of human intelligence. Adherents point to the fossil record showing an increase in average brain size over the last 200 million years. But this is an illusion that stems from the fact that larger brains are found in more recent species because large brains need time to evolve. When phylogenetic methods are applied, there is no evidence for any progressive linear trends in the evolution of intelligence leading to humans. Life on this planet resembles a branching tree – not an arrow. In short, teleological and anthropocentric notions about intelligence on Earth are not supported by any scientific evidence.

Replacing Assumptions with Scientific Data

Putting assumptions and misconceptions aside, what do we know about the evolution of intelligence on Earth from actual scientific data? Questions about the origin and evolution of intelligence on Earth are more tractable than ever before because of our sophisticated methods of

collecting, storing and analyzing large quantities of data. Although it would be impossible to document each step of this process, the question can be framed thusly: What are the major milestones and characteristics of intelligence on this planet and what do these milestones tell us about the nature of intelligence which may be relevant to astrobiology?

Before beginning, it is important to acknowledge that, with some exceptions, we cannot observe the evolution of life directly and that we must rely on inferential approaches, such as the comparative phylogenetic method. But this method does allow us to reconstruct the traits of extinct species with some degree of confidence and there are a number of scientific approaches which support informed hypotheses about the evolution of intelligence.

Brain-like functions in unicellular organisms

All organisms on Earth have the same task: to survive and reproduce. Brains exist because of the varied distribution of resources in the environment that affect survival. An immobile organism or one living in a highly predictable, stable environment would not have much need for a brain. But if one moves around then there must be a way to detect and analyze all of the varied inputs one comes in contact with and make adaptive behavioral responses to them. As such, some of the building blocks of nervous systems and brains are found in single-celled organisms. They sense their environment, briefly store the information, integrate it in different channels of input and then act upon it – producing basic adaptive behavior. These brain-like processes work at a molecular level but they reveal a common ancestry with all modern brains. One example is *Escherichia coli*, a bacterium which senses its environment through a dozen different types of protein receptors embedded in its cell wall. Each receptor specializes in a specific kind of information, e.g., toxins, sugars, amino acids, etc. The input is integrated and

the result is the “decision” to behave in a certain way, i.e., use its flagella to swim towards or away from the stimulus (Allman, 1999). Therefore, the fundamental functional properties of brains such as sensory integration, memory, decision-making, and behavior were likely present in the earliest organisms on Earth.

The property that allows unicellular organisms to detect and respond to their environment is known as “membrane excitability” and involves sensitivity to electrochemical gradients accomplished by the flow of ions into and out of the cell. This basic mechanism was later adapted to specialized cells, i.e. neurons, in metazoans. Evidence for continuity derives from the fact that the membranes of modern neurons operate by the same electrochemical principles (voltage-gated ion movement across a membrane) as in single-celled organisms (Allman, 1999). The startling conclusion from these findings is that the basic mechanism for nervous systems was already present approximately one billion years ago, when only unicellular organisms populated the earth.

Multicellularity and the First Neurons

Since its emergence in multicellular organisms 600 million years ago, the neuron has remained the basic unit of information processing in all nervous systems on Earth. A neuron is an electrochemically polarized cell with a characteristic morphology consisting of a body with branching processes containing chemical receptors. When an electrochemical threshold is reached a long axon transmits an electrical pulse to terminal branches which then release chemicals (neurotransmitters) that are picked up by the next neuron, and so forth. This highly simplified description reveals some important steps in the evolution of nervous systems. First, neurons form fiber tracts which allow information to travel along specific pathways. In the

earliest animals with nervous systems, such as jellyfish, transmission is bidirectional. In bilaterians (bilaterally symmetrical animals), neuronal transmission is unidirectional, so information flows only one way in the neuron, thus increasing the specificity of neural transmission. Second, while some animals use non-threshold graded potentials for neural transmission, at some point in evolution the neural pulse, called an action potential, became an all-or-nothing electrical phenomenon, and allowed for a new digital form of neural transmission and integration.

The first organisms to possess neurons were the earliest metazoans—those with radially symmetric bodies such as cnidarians, ctenophores, hydrozoa, etc., - appearing approximately 600 million years ago. Voltage-gated sodium channels are present in jellyfish and all brains. The neurotransmitters coursing through the brains of all modern species have precursors in single-celled organisms and were present in the nerve nets of the earliest metazoans.

Modern versions of these early taxa possess a decentralized nerve net (a loose arrangement of sensory neurons connected to motor neurons by interneurons). In many of these animals there are the very beginnings of the next step in the evolution of nervous systems, centralization, in the form of nerve rings and clusters of neurons called ganglia which allow these animals to learn and exhibit complex behaviors requiring coordination of parts of the body.

Bilateralization, Centralization, and Cephalization

Bilaterians emerged in the fossil record about 550 – 600 million years ago as early wormlike creatures with a nerve cord running down the body and enlarged ganglia (early brain) at the head region. The process is called cephalization and an anterior brain connected to a nerve

cord became the bauplan of the nervous system thereafter for all organisms with a central nervous system (Arendt et al., 2008; Striedter, 2005).

All vertebrate brains are segmented into the same parts: forebrain, midbrain, and hindbrain. And all vertebrates possess identical brain structures and functions within those segments. All mammals possess a layered neocortex (Allman, 1999) although the way the neocortex is organized or mapped in some species, such as cetaceans, is quite different, in many respects, from other species. The neocortex in all mammals, including cetaceans, is the most evolutionarily recent and pliable part of the brain and, thus, arguably, the vanguard of intelligence, i.e., the source of self-awareness, problem solving, sensory-motor integration, mental representation, etc. And despite differences in neocortical architecture, even cetaceans and primates display a striking degree of convergence in cognitive function (Marino, 2002). Likewise, invertebrate and vertebrate brains rely upon the same basic principles of information processing. All of the major vertebrate neurotransmitters, which are ultimately derived from single amino acids, are also found in invertebrate brains (Messenger, 1996) and most of them also served as signaling molecules before the first central nervous system evolved (Turlejski, 1996). Moreover, embryonic development of nervous systems across species reveals a highly conserved plan (Striedter, 2005).

There is a striking degree of conservation in the genetic mechanisms underlying nervous system formation across all species. For instance, homeotic genes that segment insect bodies are co-opted to segment parts of the vertebrate central nervous system. Other genes controlling the formation of part of the brain in fruit flies regulate the mammalian neocortex. So even the human brain, which is a very recent evolutionary development, is organized by genes with

antecedents going back half a billion years (Allman, 1999), showing that ancient conserved mechanisms underlie many of the most complex features of intelligence on earth.

Brain Size

One issue of considerable interest in discourse about intelligence on this planet is brain size. Brain size has to do with the amount of neural tissue available for information processing, under the assumption that “more is better.” Measures of brain size range from whole brain mass to the mass of specific structures in the brain to various ratios of neuron types. One measure of brain size or cephalization is the Encephalization Quotient (EQ). EQ is a measure of a species’ average brain size relative to body size taking into account brain-body allometric relations. So the EQ metric allows one to compare directly the relative brain size of a squirrel and an elephant. Species with average brain sizes have an EQ of 1. Modern humans have an EQ of 7— i.e., our brains are seven times larger than one would expect for an animal of our body size. Many cetaceans have EQs in the 4-5 range and other primates have brains 2.5 – 3 times larger than expected.

Humans like to think that our large relative brain size has allowed our species to achieve a qualitatively different intelligence from other mammals. But brain size is a continuous variable and the human brain is a product of predictable changes in brain anatomy when nonhuman anthropoid primate brains are scaled up (Sherwood et al., 2006). For instance, our degree of cortical gyrification is exactly as expected for a primate with our brain size (Zilles, 1989). Other aspects of our brain, such as relative size of our frontal lobes and the presence of specialized cells for information processing, are all either shared with other species or are expected for a primate of our body size. In summary, decades of neurobiological studies have failed to turn up a

single property of the human brain that is qualitatively different from that of other species, i.e., that is not explainable within a common framework of comparative evolution with the rest of the life forms on this planet.

Continuity of mind

As there is continuity of brain and nervous system, so is there continuity of mind. Just as in astronomy, the history of research on animal behaviour, comparative psychology and ethology is a history of de-centration. Increasing understanding of other animals has come with a dwindling of qualitative differences across species and a reframing of intelligence as a continuous character. Basic cognitive processes, such as memory and learning, are found in all animals. And, even “high-level” cognitive abilities, such as forplanning, basic arithmetic, mirror self-recognition, and the possession of a technological culture, are not unique to humans. Some of these shared capacities are reviewed here.

Intelligence in Invertebrates

Learning has been confirmed in many invertebrates including roundworms (Rankin, 2004) molluscs (Kandel, 2001) annelid worms (Friesen and Kristan, 2008), arthropods (Morse, 2000), and even the echinoderms, who lack a central nervous system (Shulgina, 2006). The basic neural mechanisms of learning are the same from molluscs to mammals (Kandel, 2009). Of considerable interest to the astrobiology community are the cephalopods (phylum Mollusca), particularly the octopus *Octopus vulgaris*, because of their complex cognitive and behavioral traits. Although octopi brains bear molluscan features, such as numerous interconnected ganglia dispersed throughout the body, they also have a highly elaborated three-lobed architecture which

gives these creatures a vertebrate-like intelligence (Hockner, 2006) evincing observational learning (Fiorito and Scotto, 1992) and even tool use (Finn et al., 2009).

Honey bee and ant colonies possess a collective memory with features shared with the individual memory system of vertebrate brains (Couzin et al., 2002); these colonies perform very similarly on a range of psychological tests (Langridge, Sedova-Franks and Franks, 2008; Passino, 2010). Importantly, collective or swarm intelligence does not necessarily emerge at the expense of individual intelligence, as individual honey bees have complex cognitive abilities (Giurfa, 2003) and learning capabilities on a par with those of vertebrates (Bitterman, 1996). Individual bees understand the concepts of ‘sameness’ and ‘difference’ (Giurfa et al., 2001), can count from one to four (Dacke and Srinivasan, 2008), and are able to accurately group visual stimuli into categories (reviewed by Benard, Stach and Giurfa., 2006), to name just a few of their prodigious abilities. Many other invertebrates, such as fruit flies and jumping spiders, possess complex cognitive abilities as well (Greenspan and Swinderen, 2004) and, like octopi, are able to learn from one another, through the use of social information (reviewed by Leadbeater and Chittka, 2009).

These findings of cognitive complexity in invertebrates reveal that the basic capacities of the human mind are demonstrable in the minds of beings who we typically view as very different from us and, in the scala natura world, vastly inferior. But scientific findings show that intelligence in many domains is ubiquitous in the animal kingdom and is shared at a very deep evolutionary level across all species.

Vertebrate Intelligence: Variations on a Theme

Setting aside the intelligence of invertebrates, complex intelligence on earth can be said to have emerged 500 million years ago with vertebrates. All vertebrate brains are variations on the same theme. Likewise, complex cognitive abilities – some found in invertebrates – are shared by all vertebrates. Most differences lie on a continuum of complexity and are shaped by the adaptive needs of each species from pre-existing characteristics. The striking implication of these facts, given the wide scope of astrobiology, is that if we were to find an extraterrestrial intelligence on another planet whose behavior paralleled the complexity of, say, a gobie using long term memory and visual geometry to navigate back to a home tidal pool, we would know, for all intents and purposes, that a human level of extraterrestrial intelligence almost certainly exists somewhere as well.

A non-exhaustive list of complex capacities found in many nonhuman vertebrate species includes the following: forplanning by chimpanzees and orangutans (Osvath and Osvath, 2008) and bottlenose dolphins (McCowan et al., 2000), mathematics by chimpanzees (Boysen et al., 1993; Tomonaga and Matsuzawa, 2000), taking the visual perspective of another by domestic pigs (Nawroth, Ebersbach and von Borell, 2014), jays (Clayton, Dally and Emery, 2007) and dogs (Kaminski, Pitsch and Tomasello, 2013), empathy in elephants (Plotnik and deWaal, 2014), understanding physical causation by chimpanzees and orangutans (Mulcahy and Call, 2006) and even intentional deception involving modeling of others' mental states by pigs (Held et al., 2000) and chimpanzees (Melis, Call and Tomasello, 2006).

In many areas of cognition members of other species either do as well, e.g. spatial learning in fishes (Brown, 2014) or exceed the capacities of adult humans, e.g., working memory for sequences of numerals by chimpanzees (Inoue and Matsuzawa, 2007) and in many perceptual domains there are no parallels in our own species, e.g., echolocation and its use in cross-modal

mental representation of objects in dolphins (Pack and Herman, 1995). All of this is not to deny the remarkable cognitive capacities of humans but, rather, to show that human intelligence is a variation on a highly conserved theme.

The “Big Five”

There are five cognitive domains in which we have, at one time or another, argued quite vociferously for human exclusivity. These are self-awareness, tool making and use, culture, numerical ability, and symbolic language. But even these impressive capacities are not unique to our species.

Self-awareness

Self-awareness is cognizance of oneself as an individual, i.e., possession of an autobiographical sense of “I”. Although all animals must have this capacity at some level, several species have demonstrated a complex human-level of self-awareness in experimental studies of mirror self-recognition (MSR), metacognition (reporting on one’s own thoughts), and other tests. MSR is the ability to recognize oneself in a mirror and is evinced by using a mirror to investigate parts of one’s body. It has been convincingly displayed in all of the great apes (Anderson and Gallup, 2011) bottlenose dolphins (Reiss and Marino, 2001), Asian elephants (Plotnik, de Waal and Reiss, 2006), and magpies (*Pica pica*) (Prior, Schwarz and Gunturkun, 2008). Bottlenose dolphins are aware of their own body parts and behaviors (reviewed by Herman, 2012). Monkeys and dolphins demonstrate abstract forms of self-awareness, such as metacognition (Smith and Washburn, 2005). Hence, a complex sense of self is shared with many other species. At this point in time our understanding of the distribution of self-awareness across

species on this planet is limited by our own species' ingenuity in developing methods to test such an abstract subjective phenomenon.

Tool Use and Making

Since the first time Jane Goodall observed wild chimpanzee David Greybeard make and use a tool (a "termite stick") in 1961 we've documented tool making and use in many primates, elephants, birds, dolphins, octopi (see above) and a host of other species. Wild gorillas use branches to gauge the depth of water when crossing streams (Breuer, Ndoundou-Hockemba and Fishlovk, 2005). New Caledonian crows create and use stick tools with their beaks to extract insects from logs (Hunt and Gray, 2003) and, in the laboratory, use analogical reasoning to use tools for accessing yet more tools (Taylor et al., 2007). A group of bottlenose dolphins off the coast of Western Australia uses pieces of sponge wrapped around their rostrum to prevent abrasions when searching for food on the sea floor (Krutzen et al., 2005).

Tool making and use is learned socially and through experimentation and involves the creation of novel solutions to various ecological problems. This basic aspect of nonhuman tool-making and use places it on a continuum with human technology and is, thus, highly relevant to hypotheses about the evolution of technological extraterrestrial intelligence. Chimpanzees are not likely to build rockets to Mars any time in the near future, but, from a psychological point of view, termite sticks and rockets are born of the same basic capacity to create something new from the environment for the purpose of achieving a specific goal – no matter how simple or complex.

Culture

The basic definition of culture is that of distinctive behavior originating in local populations and passed on through learning from one generation to the next. Culture is the main process by which behavioral innovation manifests itself. Tool-making and use is often referred to as material culture and it exists in a multitude of other species. We now know that the technology of chimpanzees (Boesch, 2012), dolphins (Krutzen et al., 2005), and New Caledonian crows (Hunt and Gray, 2003), for instance, is culturally transmitted. But culture in other behavioral domains also exists. For example, cultural transmission of specific dialects has been documented in orcas (*Orcinus orca*) (Rendell and Whitehead, 2001).

Our sophisticated linguistic abilities have allowed human cultures to become extremely complex. But the fact that cultural transmission is shared with many other species on this planet, means that we might expect the same in any extraterrestrial organism with a social bend.

Numerical Ability

Numerical ability can be categorized into several levels of complexity and abstractness. These include relative numerosness judgments, subitization (a form of pattern recognition used to rapidly assess differences among small quantities), estimation (of larger quantities), counting and sequencing, and manipulation of quantities (arithmetic). Some of the most complex and abstract numerical abilities are, not surprisingly, found in chimpanzees, who are even capable of mathematical reasoning. They can count or sum up arrays of real objects or Arabic numerals (Beran and Rumbaugh, 2001; Boysen and Bernston, 1989; Rumbaugh, Savage-Rumbaugh and Hegel, 1987)) and they display the concepts of ordinality and transitivity (the logic that if $A = B$ and $B = C$, then $A = C$) when engaged in numerical tasks, demonstrating a real understanding of the ordinal nature of numbers (Boysen et al., 1993). Chimpanzees also understand proportions

(e.g., 1/2, 3/4, etc.) (Woodruff and Premack, 1981). They can use a computer touch screen to count from 0 to 9 in sequence (Inoue and Matsuzawa, 2009; Kawai and Matsuzawa, 2000; Tomonaga and Matsuzawa, 2000). Moreover, they have an understanding of the concept of zero, using it appropriately in ordinal context (Biro and Matsuzawa, 2001).

But numerical competence is not limited to chimpanzees or great apes. Bottlenose dolphins can learn numerical concepts ((Jaakkola et al., 2005; Kilian et al., 2003) and also appear to have some understanding of the concept of zero (Herman and Forestell, 1985). Rhesus macaque monkeys are able to count to nine (Beran, 2006; Brannon and Terrace, 1998). Several species of birds (Emmerton, Lohmann and Niemann, 1997; Garland and Low, 2014; Pepperberg, 2006; Roberts, Coughlin and Roberts, 2000; Scarf and Colombo, 2011) and other species, such as lemurs (Santos et al., 2005), domestic dogs (West and Young, 2002), domestic pigs (Held et al., 2005) and, as discussed earlier, even bees (Dacke and Srinivasan, 2008) have shown numerical competencies, including, in some cases, counting and simple arithmetic.

Symbolic Communication

Most natural communication systems on this planet, including human language, derive from common principles of communication and information theory, allowing all organisms to accomplish similar basic communicative feats. But the comprehension and use of symbols is thought to be the defining characteristic of human language, allowing us to express abstract ideas, discuss objects and events which are not present in space and time, and, giving us the ability to create an unlimited set of utterances. This quality facilitates the cultural transmission of ideas, as mentioned above.

There have been numerous studies showing that members of other species can acquire a symbolic artificial language, including dolphins, who comprehend grammatical sentence structure (reviewed by Herman, Pack and Morrell-Samuels, 1993), chimpanzees (reviewed by Rumbaugh, Beran and Savage-Rumbaugh, 2003), African Grey Parrots (Pepperberg, 2002) and many others. Importantly, chimpanzees in captivity use the symbolic elements of language in every-day settings (Lyn et al., 2011; Rumbaugh et al., 2003). Moreover, the symbolic element that is key to human culture is also found, though to a much more limited degree, in wild chimpanzees. For instance, in one chimpanzee group arbitrary symbolic gestures are used to communicate desire to have sex whereas in another group an entirely different symbolic gesture is used to express the same sentiment (McGrew, 2011). The presence of symbolic culture in chimpanzees demonstrates that abstract concepts can be present without human language.

There are several points about communication capacities in other species relevant to astrobiology. First, the natural communication systems of many other species share features of human language. Second, we have vastly incomplete knowledge of the nature of communication in some groups of animals, e.g., cetaceans. Third, members of other species can comprehend and use symbols and human language in appropriate settings and, thus, do possess the capacity to think in symbolic terms. Fourth, chimpanzees use symbolic gestures in cultural settings. Fifth, while symbolic communication has clearly become the forte' of the human species, it is not entirely outside the range of mental capacities of many other species. Sixth and most important is that the human ability to communicate with a symbolic language could only have come from shared characteristics with other species.

This review began with the question of why the serious study of intelligence has been ignored by the astrobiology community and has provided abundant evidence that it is not for lack of empirical data, accessibility or scientific tractability. Instead, there appear to be other drivers behind this omission having to do with misconceived models of human nature, particularly the *scala natura*, and the unsupported assumptions they lead to. These notions lead to ways of thinking which block the path to open scientific inquiry about intelligence in astrobiology.

Quite to the contrary, the existing body of scientific knowledge on the evolution of intelligence makes clear several points which support and urge the study of intelligence in astrobiology. These points include the following. There are no scientifically valid reasons for treating the human brain and intelligence as either a unique or singular case. The human brain can only be understood in the same evolutionary-comparative framework as the rest of life on earth. All nervous systems on earth are governed by the same electrochemical principles of information processing laid down well over one billion years ago. Once the basic plan for brains evolved, everything that came afterward is a variation on a highly conserved theme. Thus, there is a surprising degree of shared cognition across invertebrates and vertebrates. There are, of course, differences in intelligence and mind across species but they all can be understood in a common framework.

All of this knowledge should exhort the realization that the central question in astrobiology “Are we alone?” has already been answered. We are not. Thus, astrobiology should embrace the study of intelligence as a ubiquitous property of life and one that converts the current impasse to relevant and exciting opportunities for further exploration.

References

- Allman, J. M. 1999. *Evolving Brains*. New York: Scientific American Library.
- Arendt, Detlev, Deans, A., Jekely, G., and Tessmar-Raible, K. 2008. "The Evolution of Nervous System Centralization." *Philosophical Transactions of the Royal Society B: Biological Sciences* **363**(1496): 1523-1528
- Benard, J., Stach, S., and Giurfa, M. 2006. "Categorization of Visual Stimuli in the Honey Bee, *Apis mellifera*." *Animal Cognition* **9**: 257-270.
- Beran, M.J. 2006. Quantity perception by adult humans (*Homo sapiens*), chimpanzees (*Pan troglodytes*), and rhesus macaques (*Macaca mulatta*) as a function of stimulus organization. *International Journal of Comparative Psychology* **19** (4): 386-297.
- Beran, M.J. and Rumbaugh, D.M. 2001. Constructive enumeration by chimpanzees on a computerized task. *Animal Cognition* **4**: 81-89.
- Biro, D. and Matsuzawa, T. 2001. Use of numerical symbols by the chimpanzee (*Pan troglodytes*): Cardinals, ordinals and the introduction of zero. *Animal Cognition* **4**: 193-199.
- Bitterman, M.E. 1996. Comparative analysis of learning in honeybees". *Learning and Behavior* **24**(2): 123-141.
- Boesch, C. 2012. *Wild Cultures*. Cambridge: Cambridge University Press.
- Boysen, S. T., Bernston, G., Shreyer, T. and Quigley, K. 1993. Processing of ordinality and transitivity by chimpanzees (*Pan troglodytes*)." *Journal of Comparative Psychology* **107**: 208-216.
- Boysen, S.T. and Bertson, G.G. 1989. Numerical competence in a chimpanzee (*Pan troglodytes*). *Journal of Comparative Psychology* **103**(1): 23-31.
- Boysen, S.T., Berntson, G.G., Shreyer, T.A. and Quigley, K.S.1993. Processing of ordinality and transitivity by chimpanzees (*Pan troglodytes*). *Journal of Comparative Psychology* **107**: 208-216.
- Brannon, E.M. and Terrace, H.S. 2000. Representation of the numerosities 1-9 by rhesus macaques (*Macaca mulatta*). *Journal of Experimental Psychology: Animal Behavior Processes*, **26**, 31-49.
- Breuer, T., Ndoundou-Hockemba and Fishlovk, V. 2005. "First Observation of Tool Use in Wild Gorillas." *PLoS Biology* 3(11): e380. doi:10.1371/journal.pbio.0030380
- Brown, C. 2014. "Fish intelligence, sentience and ethics." *Animal Cognition* doi 10.1007/s10071-014-0761-0
- Clayton, N. S., Dally, J. and Emery, N. 2007. Social cognition by food-caching corvids. The Western scrub-jay as a natural psychologist." *Philosophical Transaction of the Royal Society B* **362**(1480): 507-522.
- Couzin, I. D., Krause, J., James, R., Ruxton, G.D. and Franks, N. 2002. Collective memory and spatial sorting in animal groups." *Journal of Theoretical Biology* **218**(1): 1 – 11.
- Crowe, M. J. 2008. *The Extraterrestrial Life Debate: Antiquity to 1900: A Source Book*. Notre Dame: University of Notre Dame Press.
- Dacke, M. and Srinivasan, M. 2008. Evidence for counting in insects. *Animal Cognition* **4**: 683-689.

- Darwin, C. 1871. *The Descent of Man, and Selection in Relation to Sex* (1st ed.). London: John Murray.
- Darwin, C. 1859. *On the Origin of Species by Means of Natural Selection, or the Preservation of Favoured Races in the Struggle for Life* (1st ed.). London: John Murray.
- Emmerton, J., Lohmann, A. and Niemann, J., 1997. Pigeons' serial ordering of numerosity with visual arrays. *Animal Learning and Behavior* **25**, 234–244.
- Finn, J., Tregenza, T. and Norman, M.D. 2009. Defensive tool use in a coconut-carrying octopus." *Current Biology* **19**(23): R1069–R1070.
- Fiorito, G. and Scotto, P. 1992. Observational learning in *Octopus vulgaris*. *Science* **256**, 545–546.
- Friesen, W. Otto, et al. 2008. "Leech Locomotion: Swimming, Crawling, and Decisions." *Current Opinion in Neurobiology* **17**(6): 704–711.
- Garland, A. and Low, J. 2014. Addition and subtraction in wild New Zealand robins. *Behavioural Processes*.
<http://www.sciencedirect.com/science/article/pii/S0376635714001909>
- Giurfa, M., Reisenman, S. M., Gerber, B. and Lachnit, H. 2003. The effect of cumulative experience on the use of elemental and configural visual discrimination strategies in honeybees. *Behavioral Brain Research* **145**: 161-169.
- Giurfa, M., Zhang, S., Jenett, A., Menzel, R. and Mandyam, V.S. 2001. The concepts of 'sameness' and 'difference' in an insect. *Nature* **410**: 930-933.
- Greenspan, Ralph J. and Swinderen, Bruno van. 2004. Cognitive consonance: Complex brain functions in the fruit fly and its relatives. *Trends in Neurosciences* **27**(12): 707-711.
- Held, S., Baumgartner, J., Kilbride, A., Byrne, R.W. and Mendl, M. 2005. Foraging behaviour in domestic pigs (*Sus scrofa*): Remembering and prioritizing food sites of different value. *Animal Cognition*, **8**: 114-121.
- Held, S., Mendl, M., Devereux, C. and Byrne, R.W. 2000. Social tactics of pigs in a competitive foraging task: the 'informed forager' paradigm. *Animal Behaviour*, **59**, 579-576.
- Herman, L. M. 2012. Body and self in dolphins. *Consciousness and Cognition* **21**: 526–545.
- Herman, L.M. and Forestell, P.H. 1985. Reporting presence or absence of named objects by a language-trained dolphin. *Neuroscience and Biobehavioural Reviews* **9**: 667–691.
- Herman, L.M., Pack, A.A. and Morrel-Samuels, P. 1993. Representational and conceptual skills of dolphins. In Roitblatt, H.R. *et al.* Language and Communication: Comparative Perspectives. Hillsdale, New Jersey: Erlbaum, pp. 273-298.
- Hochner, B. 2006. The Octopus: A model for a comparative analysis of the evolution of learning and memory mechanisms. *Biological Bulletin* **210**(3): 308.
- Hunt, G.R. and Gray, R.D. 2003. Diversification and cumulative evolution in New Caledonian crow tool Manufacture." *Proceedings of the Royal Society of London B* **270**(1517): 867-874.
- Inoue, S. and Matsuzawa, T. 2007. Working memory of numerals in chimpanzees." *Current Biology* **17**(23): R1004-R1005.
- Inoue, S. and Matsuzawa, T. 2009. Acquisition and memory of sequence order in young and adult chimpanzees (*Pan troglodytes*). *Animal Cognition* **12**(1): S58-S69.
- Jaakola, K., Fellner, W., Erb, L., Rodriguez, M. and Guarino, E. 2005. Understanding of the concept of numerically "less" by bottlenose dolphins (*Tursiops truncatus*). *Journal of Comparative Psychology* **119**: 296–303.

- Kaminski, J. Pitsch and Tomasello, M. 2013. Dogs Steal in the Dark. *Animal Cognition* **16**: 385-394.
- Kandel, E. R. 2009. The biology of memory: A forty year perspective. *The Journal of Neuroscience* **29**(41): 12748-12756.
- Kandel, Eric R. 2001. The molecular biology of memory storage: A dialogue between genes and synapses. *Science* **294**(5544): 1030 - 1038.
- Kawai, N. and Matsuzawa, T. 2000. Numerical memory span in a chimpanzee. *Nature* **403**: (6): 39-40.
- Kilian, A., Yaman, S., von Fersen, L. and Gunturkun, O. 2003. A bottlenose dolphin discriminates visual stimuli differing in numerosity. *Learning and Behaviour* **31**: 133–142.
- Krutzen, M., Mann, J., Heithaus, M.R., Connor, R.C., Bejder, L. and Sherwin, W.B. 2005. Cultural transmission of tool use in bottlenose dolphins. *Proceedings of the National Academy of Sciences* **102**(25): 8939-8943.
- Langridge, E. A., Sendova-Franks, A.B. and Franks, N.R. 2008. How experienced individuals contribute to an improvement in collective performance in ants.” *Behavioral Ecology and Sociobiology* **62**: 447-456.
- Leadbeater, E. and Chittka, L. 2009. Bumble bees learn the value of social cues through experience.” *Biology Letters* **5**: 310-312.
- Lyn, H., Greenfield, P.M., Savage-Rumbaugh, S., Gillespie-Lynch, K. and Hopkins, W.D. 2011. Nonhuman primates do declare! A comparison of declarative symbol and gesture use in two children, two bonobos, and a chimpanzee. *Language and Communication* **31**: 63-74.
- Marino, L. 2007. Scala natura”. In Bekoff, M. *The Encyclopedia of Human-Animal Relationships*. Westport, CT: Greenwood Publishing Group, pp. 220-224.
- Marino, L. 2002. Convergence in complex cognitive abilities in cetaceans and primates.” *Brain, Behavior and Evolution* **59**: 21-32.
- McCowan, B., Marino, L. Vance, E., Walke, L. and Reiss, D. 2000. Bubble ring play of bottlenose dolphins: Implications for cognition. *Journal of Comparative Psychology* **114**: 98-106.
- McGrew, W.C. 2011. *Pan symbolicus*. A cultural primatologist’s viewpoint. In: Henshilwood, C.S. and d’ Errico, F. *Homo Symbolicus: The Dawn of Language, Imagination and Spirituality*. John Benjamins: Amsterdam, pp. 1-12.
- Melis, A. P., Call, J. and Tomasello, M. 2006. Chimpanzees (*Pan troglodytes*) conceal visual and auditory information from others.” *Journal of Comparative Psychology* **120**(2): 154-162.
- Messenger, J. B. 1996. Neurotransmitters of cephalopods. *Invertebrate Neuroscience* **2**: 95-114.
- Morse, D. H. 2000. The effect of experience on the hunting success of newly emerged spiderlings. *Animal Behavior* **60**(6): 827-835.
- Mulcahy, N. and Call, Josep. 2006. How great apes perform on a modified trap tube task.” *Animal Cognition* **9**:193 – 199.
- Nawroth, C., Ebersbach, M. and von Borell, E. 2014. Juvenile domestic pigs (*Sus scrofa domestica*) use human-given cues in an object choice task.” *Animal Cognition* **17**(3): 701-713.
- Osvath, M. and Osvath, H. 2008. Chimpanzee (*Pan troglodytes*) and orangutan (*Pongo abelii*) forethought: Self-control and pre-experience in the face of future tool-use. *Animal Cognition* **11**: 661-674.

- Pack, A. A. and Herman, L.M. 1995. Sensory integration in the bottlenose dolphin: Immediate recognition of complex shapes across the senses of echolocation and vision.” *Journal of the Acoustical Society of America* **98**: 722-733.
- Passino, Kevin M. 2010. “Honey Bee Swarm Cognition: Decision Making Performance and Adaptation.” *International Journal of Swarm Intelligence* **1**(2): 18 pgs.
- Pepperberg, I. M., 2006. Ordinality and inferential abilities of a grey parrot (*Psittacus erithacus*). *Journal of Comparative Psychology* **120** (3), 205–216.
- Plotnik, J. M. and de Waal, F. B.M. 2014. Asian elephants (*Elephas maximus*) reassure others in distress. *PeerJ* **2**: e278, doi 10.7717/peerj.278
- Plotnik, J. M., de Waal, F.B.M. and Reiss, D. 2006. Self-recognition in an Asian elephant. *Proceedings of the National Academy of Sciences* **103**(45): 17052-17057.
- Prior, H., Schwarz, A. and Gunturkun, O. 2008. Mirror-induced behavior in the magpie (*Pica pica*): Evidence of self-recognition.” *PLoS Biology* **6**(8): e202. doi: 10.1371/journal.pbio.0060202
- Reiss, D. and Marino, L. 2001. Self-recognition in the bottlenose dolphin: A case of cognitive convergence. *Proceedings of the National Academy of Sciences USA* **98** (10): 5937-5942.
- Rendell, L. and Whitehead, H. 2001. Culture in whales and dolphins. *Behavioural and Brain Sciences* **24**: 309-324.
- Roberts, W.A., Coughlin, R. and Roberts, S., 2000. Pigeons flexibly time or count on cue. *Psychological Science* **11** (3): 218–222.
- Rumbaugh, D. M., Beran, M. J. and Savage-Rumbaugh, E. S. 2003. Language. In D. Maestriperi, *Primate Psychology*, Harvard University Press: Cambridge, Mass., pp. 395-423.
- Rumbaugh, D.M., Savage-Rumbaugh, S., and Hegel, M.T. 1987. Summation in the chimpanzee (*Pan troglodytes*). *Journal of Experimental Psychology: Animal Behaviour Processes* **13**(2): 107-115.
- Santos, L.R., Barnes, J.L and, Mahajan, N. 2005. Expectations about numerical events in four lemur species (*Eulemur fulvus*, *Eulemur mongoz*, *Lemur catta* and *Varecia rubra*). *Animal Cognition* **8**(4): 253–262.
- Scarf, D., Hayne, H. and Colombo, M. 2011. Pigeons on par with primates in numerical competence. *Science* **334**(6063): 1664.
- Sherwood, Chet C. et al. 2006. “Evolution of Increased Glia-Neuron Ratios in the Human Frontal Cortex. *Proceedings of the National Academy of Sciences USA* **103**: 13606-13611.
- Shulgina, G. I. 2006. Learning of inhibition of behavior in the sea star, *Asterias rubens*. *Comparative and Ontogenic Physiology* **42**(2):161-165.
- Smith, J. D. and Washburn, D. A. 2005. Uncertainty monitoring and metacognition by animals.” *Current Directions in Psychological Science* **14**: 19-24.
- Striedter, G. F. 2005. *Principles of Brain Evolution*. Sunderland, Mass.: Sinauer Associates.
- Taylor, A., Hunt, G., Holzaiider, J.C. and Gray, R.D. 2007. Spontaneous metatool use by New Caledonian crows.” *Current Biology* **17**(17): 1504-1507.
- Tomonaga, M. and Matsuzawa, T. 2000. Sequential responding to arabic numerals with wild cards by the chimpanzee. *Animal Cognition* **3**: 1-11.
- Turlejski, K. 1996. Evolutionary ancient roles of serotonin: Long-lasting regulation of activity and development. *Acta Neurobiologiae Experimentalis* **56**: 619-636.

- West, R.E., Young, R.J. and 2002. Do domestic dogs show any evidence of being able to count? *Animal Cognition* **5**(3), 183–186.
- Woodruff, G. and Premack, D. 1981 Primitive mathematical concepts in the chimpanzee: Proportionality and numerosity. *Nature* **293**: 568-570.
- Zilles, K. 1989. Gyrfication in the cerebral cortex of primates. *Brain, Behavior and Evolution* **34**(3): 143-150.