Aliens Are Likely to Be Smart But Not "Intelligent": What Evolution of Cognition on Earth Tells Us about Extraterrestrial Intelligence

Anna Dornhaus
University of Arizona, USA

Abstract

How likely is it that we will find aliens like the ones in so many science fiction stories–people who possess self-awareness and cognitive ability comparable to ours, but who arose from an independent evolutionary origin? Here I make the argument that if life has evolved on other planets, it may well eventually acquire complexity equivalent to that found on Earth. The resulting lifeforms may be good problem-solvers, including predicting their environment and the behavior of social partners, using tools, learning, and otherwise flexibly and adaptively responding to information: these are all traits common among organisms on Earth. However, on Earth, human-like intelligence is unique. No other animal appears to have the same level of cognitive complexity, ability to use abstract and endlessly flexible communication, and ability to capitalize on social division of labor as humans do. Surprisingly, we do not know why this is the case: why are we the only ones with this level of intelligence on our own planet? This is not an unsolvable question in principle: we know the answer to many evolutionary "why" questions when it comes to animal intelligence. In the case of humans, however, natural selection to increase individual reproduction seems insufficient as explanation. Perhaps it is: sexual selection, the evolution of an exaggerated trait unnecessary for survival but impressive to potential mates, much like a peacock's tail or a nightingale's song, may be the most plausible explanation for the evolution of the human brain. If this is true, then we should expect cognitive ability, i.e. learning, memory, abstraction, and many other elements of intelligence to be commonplace in the galaxy as they are among organisms on Earth; but exaggerated intelligence as in humans may be a rare accident of chance, as rare as a peacock's tail.

Introduction

When we finally discover life on another planet (or moon), will it be an alien civilization with which we can have an intellectual exchange of ideas, or will it be something we study in a test tube? Here I discuss what we know about how likely it is, given that life has evolved on a planet, that this life will develop into something like humans. I'll first mention different aspects of what might be called "intelligence," and where and why we find them on Earth. Then I'll discuss what is unique about human intelligence, and why it appears to be unlikely to evolve.

Intelligence That Is Not Human

What is intelligence? There is no generally agreed-upon definition, but intuitively the concept refers either to advanced cognitive ability or to consciousness. Cognitive ability, roughly, is the ability to solve problems with a nervous system (although there are exceptions, e.g. in collective (Reid et al. 2012) or artificial intelligence (Lindley 2013), or when referring to microbes or plants (Trewavas 2016); see particularly (Baluška and Mancuso 2009) for a broader perspective). For example, this might include specific skills such as navigation, recognition of social partners, or counting, or general abilities such as generalization, learning, ability to solve novel problems by insight, etc. (Shettleworth 1998; I discuss consciousness below). Many of these skills imply that information is received through sensory organs, processed in some way, and a motor response generated. Generally "more intelligent" is thought to imply more complex such information processing (not simply learning speed, Chittka et al. 2012); in terms of the observed outcome, generally more flexible behavior and more generalized problem-solving skills are considered more "intelligent" (Matzel and Kolata 2010, Gould 2004).

There is abundant evidence that intelligence, in this sense, cannot be reduced to a binary present/absent distinction. Biology and psychology have a history of attempting to define human uniqueness in terms of some specific cognitive skill that non-human animals are simply not capable of: this approach has repeatedly failed (rev. in Gould 2004; e.g. with regard to tool use (Goodall 1964, Krützen et al. 2005, Weir et al. 2002); theory of mind (Call and Tomasello 2008, Dally et al. 2010) although see (Penn and Povinelli 2007); use of communication signals that are abstract representations of their content (Frisch 1967, Seyfarth et al. 1980, Janik 2013, Slobodchikoff et al. 1991, Ausmus and Clarke 2014); episodic memory (Griffiths et al. 1999, Dere et al. 2006); or metacognition (Dornhaus and Franks 2008, Liu et al. 2016, Sayers et al. 2015)). In addition, many cognitive skills which we realized were present not only in humans but also in non-human primates have now been demonstrated in animals that are much more distantly related to humans, and sometimes even been shown to be common in arthropods (rev. in Dornhaus and Franks 2008, Greenspan and van Swinderen 2004, Chittka 2023); e.g. social learning and teaching (Dunlap et al. , Richardson et al. 2007); generalization (Wehner 1971, Liu et al. 1999); tools (Morrill 1972); cognitive maps (Menzel et al. 2000); individual recognition (Tibbetts 2002); planning or latent learning (Franks et al. 2007, Tarsitano and Jackson 1997); analogical reasoning (Giurfa et al. 2001, Zhang et al. 2005)). However, it is clear that while we find a variety of such cognitive skills present across different species of animals, we also find many species that lack some or all of these skills, and the presence of one specific cognitive ability is not a good predictor of other such abilities (Gingins and Bshary 2016).

The probability of non-human-like intelligence

The field of behavioral ecology, or more specifically cognitive ecology, studies what conditions promote the evolution of intelligence generally or with regard to any of the specific skills listed above (Dukas 2004, 2008). Note that evolved intelligence is intelligence that has served to maximize reproduction of the line that carries it; evolution does not promote open-ended increases in intelligence (or any other trait) [1]. In other words, under which conditions is the gain in individual reproduction achieved with a cognitive skill worth the costs of this skill? Answering this question requires understanding both the costs (e.g. Johnston 1982, Mery and Kawecki 2003) and the benefits of "intelligence". "Constitutive" costs are those that are paid up-front, whether or not a skill is used. This might include the cost of building neural tissue, elaborate sensory organs, etc., and the costs of maintaining them even when not used. "Induced" costs are those that are paid when a cognitive skill is used, such as the energy costs of firing neurons (Mery and Kawecki 2004). Importantly, some of the most important costs of behavioral flexibility and learning may not be physiological, but include opportunity costs (e.g. spending time to collect information instead of food) and costs of mistakes (when something has not yet

[1] How evolution works: A defining characteristic of life is that it evolves (Mix 2014); one might argue this is the only definition of life we need (I would). Evolution is the logically necessary consequence of reproduction with inheritance and variation: any heritable variant of a trait that increases the chance that more individuals in the next generation will have the same heritable trait variant will increase in frequency over time. This is why a lot of biological articles on evolution of cognition focus on demonstrating variation and heritability. That variants producing more offspring will be more frequent in the next generation sounds obvious, but has non-obvious implications. First, all that matters for evolutionary optimization is individual reproduction, not any other performance measure such as survival or harmony with others. Although what is considered an individual can be tricky (essentially it is the unit that is reproducing with variation and inheritance), it is generally not the species. This means traits do not evolve because they promote the survival or spread of a particular type of animal, but do so because they promote the reproduction of the particular individual, or gene, that carries them. In an extreme example, biological species can and have evolved themselves into extinction ("evolutionary suicide", Rankin and López-Sepulcre 2005; this is possibly the reason for the extinction of sabertoothed tigers, for example (Van Valkenburgh, Wang, and Damuth 2004)).

been learned, Shettleworth et al. 1988). To illustrate this, think of bees. Bees eat only nectar and pollen, and thus have to find flowers to extract their food. Some bees, like solitary cactus bees in the Southwestern US, are specialized on a single species of cactus (McIntosh 2005). They thus need no flexibility, but are genetically preprogrammed to identify exactly what their food sources look like and how to handle them. Bumble bees, on the other hand, are typically generalists: they can learn to extract food from any type of flower as well as many contraptions built by scientists, such as tunnels and mazes (Chittka 2023). A naive bumble bee or honey bee, however, may spend quite a while learning what a flower is (Gil et al. 2007, Menzel and Giurfa 2001) and how to handle a particular type (Raine and Chittka 2006, Muth et al. 2015). Which is the better strategy long-term? In a long-term fixed environment, preprogrammed behavior is better—cactus bees may have a neural system that is optimized for the single function of finding cactus flowers, and that is likely highly efficient at this (Bernays 1999, Laverty and Plowright 1988). The cactus bee does not waste time with things that are not cactus flowers or flowers at all, and makes very few mistakes. However, bumble bees, because of their ability to use a much broader spectrum of nectar and pollen sources, are able to populate a much more diverse set of environments, and presumably will thrive more easily in environments that are changing (Stephens 1991, Austin and Dunlap 2019).

Why then do some animals become like cactus bees, and others like bumble bees? Biologists have good explanations in hindsight about how some lifestyles and environments promoted the evolution of behavioral flexibility. For example, organisms that are generalists with regard to food sources and habitats used tend to rely more on learning and plastic (i.e. not innately fixed) behavioral strategies; this is especially the case for extractive foragers, i.e. animals which have to manipulate their catch in various ways to extract food (Navarrete et al. 2016). Second, the frequency and predictability of environmental change over spatial and temporal scales has a strong impact on the potential benefits and costs of learning: environments that are fixed over many generations produce organisms that are hardwired for the best strategies in that environment (Stephens 1991). On the other hand, in some environments, within an individual's lifetime, the best strategy changes so fast, or the cues that allow a decision about which strategy to use are so unreliable, that learning does not evolve either, and individuals are better off choosing randomly (Dunlap and Stephens 2009). For example, stickleback fish living in the open water do not get reliable cues to orient to, and thus did not evolve this skill; other sticklebacks living near lake bottoms, however, have very good landmark learning and orientation skills (Odling-Smee et al. 2008). Thus, only when the best strategy is somewhat predictable from sensory information, but not fixed over evolutionary timescales, do we expect organisms to evolve behaviors reliant on learning.

What can we conclude from this about evolution of intelligence on other planets? There are two major problems that make any kind of prediction difficult. The first is that a biologist's understanding of "environment" is sometimes better described as ecological niche (Peterson et al. 1999, Kerr and Feldman 2003): it does not necessarily refer to a geographic environment (e.g. climate, geochemistry, or topography, things we might be able to figure out for alien planets), but to everything important to the organism, such as food sources, predators, availability of nest sites, etc. – in other words to the presence and composition of other biological species it might encounter. It is thus quite possible that the same geographic area contains species that live in a stable environment and species that live in a highly fluctuating environment, as determined by the temporal dynamics of their respective ecological niches. It is unlikely that we would be able to predict, from astronomically observable traits of planets, what types of environments (with regard to, for example, predictability of food) any local organisms will encounter. In current biology, there is not even a consensus on how and why environmental variables and gradients on Earth affect even large-scale patterns such as species diversity (e.g. Latham and Ricklefs 1993, Gaston 2000, Michalet et al. 2006), something that is much easier to measure than temporal or spatial heterogeneity, or the predictability of resources and other ecological factors for individual species.

The second problem is that of contingency in evolution. It is already well-known that the specific morphological, behavioral, and ecological characteristics of living species are the result of their specific history, including stochastic events along the way – and thus impossible to predict from any amount of knowledge about the ancestor and habitat they started in. This implies that *predicting*, rather than *explaining* in hindsight, the evolution of a lifestyle that requires intelligence is impossible. Closely related species may repeatedly evolve or lose particular skills (Sherry et al. 1992, Gingins and Bshary 2016); even within the same individual organism, if local/current conditions change the benefits of a particular skill, that skill, and even the associated part of the brain, may disappear only to be rebuilt again later (Galea and McEwen 1999, Galea et al. 1994). In addition, animals may use fixed strategies or rules-of-thumb that generate approximately correct behavior in expected environments (Fawcett et al. 2013, 2014). Similarly, many animals have evolved specific cognitive problem-solving skills but not others: the reed warbler, a bird parasitized by another bird, the cuckoo, can discriminate cuckoo eggs from its own even though the differences are extremely subtle; but it is apparently fooled by the cuckoo chick, which looks nothing at all like its own chicks (in this particular case, the likely explanation is that a highly efficient first line of defense (egg recognition) prevents the evolution of an effective second line of defense (chick recognition) because that second line of defense is so rarely needed that it fails to exert significant selection pressure, Kilner and Langmore 2011, Grim 2006).

In summary, cognitive ecology has provided abundant evidence that cognitive skills evolve to be finely tuned to their benefits and costs, and many cognitive skills have evolved repeatedly across a wide variety of organisms. When we know what an organism's ecological niche is, we know something about what kinds of cognitive skills to expect; but the ecological niche of an organism cannot be predicted from its abiotic environment (in fact biologists speak of 'niche construction', as a process driven by the organism not the environment, Day et al. 2003). In addition, cognitive skills may quickly and repeatedly evolve and disappear depending on how much they increase individual reproductive success in a given context.

A side note on "complexity"

A characteristic of life on Earth is high complexity compared to non-life. Without attempting to define this exactly, life is diverse (many types of life), made up of interacting units at several levels of organization (molecules interacting to form cells, cells interacting to form animals/plants, interacting species form ecosystems), and behaves in ways that are both less random and less predictable than behaviors of solids, liquids, and gases—all of this can be thought of as contributing to the complexity of life. Many complex systems are self-organized, in that their operation is not organized hiarchically, but instead the problem-solving ability of the system is produced by the distributed actions and interactions of its parts–this is in essence also how nervous systems, and brains, work. The distributed nature of intelligence is sometimes more obvious than other times, e.g. also in social insect colonies, which, for example, arrive at consensus decisions in much the same way as a brain does (Marshall et al. 2009).

Biologists have not made much progress understanding the evolution of complexity: that is, even more so than for intelligence, we do not know which environmental conditions (biotic or abiotic) promote or prevent complexity. However, like non-human intelligence, complexity has emerged repeatedly in different lineages of life and in different environments. One might argue that, across Earth's history, complexity initially increased first slowly and then rapidly (e.g. the number of species has increased at the fastest rate in most recent geological records, at least until the advent of humans). Such a pattern suggests an exponential function, which is typically generated by a positive feedback; i.e. complexity may promote the evolution of more complexity. If that's the case, how common complex life is on other planets may depend a lot on how long it has been there.

Human-like Intelligence

It has been surprisingly difficult to define cognitive skills that human brains can do that insect brains cannot, despite the fact that insect brains have around on the order of 100,000 (10^5) neurons and human brains have around 1 billion (10^9). This indicates that many aspects of "intelligence" may not require a large brain, and that we understand little about what size brain is needed for particular cognitive skills (Chittka and Niven 2009, Chittka 2023). But it may also indicate that searching for qualitatively different processes to define human intelligence is the wrong approach (Lindley 2013, Shettleworth 2010). Quantity matters, too: human brains are built from the same toolkit (cell types, genes) as other animal brains, but more cells, or more connections, may enable ultimately significantly, even qualitatively different outcomes (Mashour and Alkire 2013, Roth and Dicke 2005). Non-human animals show the ability to generalize or learn concepts (Giurfa et al. 2001); but human capacity for abstract thought and behavioral flexibility is unmatched (Matzel and Kolata 2010, Penn and Povinelli 2007). Non-human animals communicate, including with symbols (Frisch 1967); but the human capacity for expressing complex and novel types of information with language is unlike the communication systems of any other species on Earth (Hauser et al. 2002. Non-human animals exhibit social learning, in that their behavior can be affected by the behavior of others (Leadbeater and Chittka 2007); however, the richness and complexity of information and training that humans are able to pass on to other humans is unrivalled (Tomasello et al. 1993).

Consciousness

This chapter largely equates intelligence with cognitive problem solving. However, in common parlance, many people use the term "intelligence" to imply consciousness, which is also often considered a quintessentially human trait. Consciousness is typically understood as having any internal perspective (it is like something to be you – or a bat; Nagel 1974). However, so far, this phenomenon evades scientific study (Cohen and Dennett 2011; although progress is, perhaps, being made, Boly et al. 2013, Northoff and Lamme 2020). We don't have an operational definition or know how to measure whether it is present (a practical problem for example for anesthesiologists; Bayne et al. 2016). Some argue it ubiquitous, a necessary side-effect of any complex information processing (Trewavas and Baluška 2011); some argue that there is evidence for consciousness in non-human animals (Barron and Klein 2016, Griffin and Speck 2004, Greenspan and van Swinderen 2004) or plants (Trewavas 2016); others believe it entirely optional even for human-like brains (although see Dennett 1995). Evolutionary biologists argue from plausibility that if humans have it, it must be good for something; and from homology that, since most other human cognitive traits also occur in non-human animals, at least some animals probably also have some form of consciousness. Empirical attempts to study it usually center on testing for self-awareness or episodic memory of some kind (rev. in Gallup and Anderson 2018, Allen and Fortin 2013; these, however, do not encompass everything commonly considered 'consciousness'). No test for the benefits of consciousness, compared to an organism of similar intelligence but that lacks consciousness, has been developed. Given this, we can make no statements about what causes consciousness to evolve; therefore we can also make no statements about the probability that extraterrestrial organisms would possess it.

"Intentionality" is also sometimes used to distinguish human from non-human behavior. However, as philosophers typically conceive it, intentionality implies "free will," the ability to make decisions and act independently of any physical or physiological processes in the brain (or body). This essentially requires the assumption that we live in a dualistic (i.e. not merely material) world (or a purely spiritual one). If this is true, current science is missing a fundamental part of how the world works, and we certainly have no reason to think we can predict how other worlds work. Biologists, on the other hand, generally use the term "intention" as implying evolved goal-seeking, which we expect in any biological organism (Heisenberg 2014, Sayers et al. 2015, Barron and Klein 2016), including extraterrestrial ones.

The human global impact

If intelligent aliens were to visit Earth, the most obvious characteristic of humans is not their individual intelligence, but their impact on the whole planet. China's Great Wall may be one of the few man-made individual structures visible from space, but the lights at night, the atmospheric composition, the fact that human-domesticated mammals on Earth outweigh wild land mammals about 10:1, and the ubiquitous covering of Earth's surface with asphalt and buildings generally are all evidence that humans have changed their environment at a global scale. However, this is not clearly related to cognition; and again, it is the quantity rather than the quality that seems uniquely human. For example, social insects also change their local environments (from temperature-controlled nests to removing 'weeds' that are in their way or 'farming' other arthropods), and microbes may induce cloud formation or generate locally toxic ocean water to increase their food abundance (by killing fish), to say nothing of the fact that we owe our atmospheric oxygen to photosynthetic cyanobacteria – which, in generating it, also caused a major mass extinction (of other, oxygen-intolerant bacteria) and forever changed Earth's biosphere's evolutionary trajectory (similar to the algae who's buried skeletons removed carbon from the atmosphere at a global scale). Instead of intelligence, the primary factor typically identified as cause of our, human, global impact is our mutualism with domesticated species, i.e. food plants and animals (Diamond 2002, Boivin et al. 2016).

The second deciding factor is likely cooperation and culture. The evolution of cooperation is not straightforward, but nonetheless well-studied both theoretically and empirically (e.g. Dugatkin 1997, Smaldino and Schank 2012, Pereda et al. 2017), and the study of 'cultural evolution', i.e. non-genetic transmission of, and successive building on, skills and behavioral traits, is a current focus of much research (Tomasello et al. 1993, Koops et al. 2014, Mesoudi 2015). It is unclear what, exactly, caused humans to evolve their unusually high degree of cooperation among non-relatives, as well as their ability to genuinely imitate, i.e. observe and 'understand' how another individual solved a problem and learn from it. However, there is broad consensus that these traits are both especially, perhaps even uniquely, human, as well as essential for our species' ecological success (Kramer 2010, Tennie et al. 2009, Pereda et al. 2017). Cooperation is in fact so engrained in our understanding of who we are that misconceptions about it are widespread, including, or perhaps especially, among people interested in ETIs

(Tipler 1981 already admonished physicists and philosophers that they 'think they know more about biology than biologists'). In particular, 'intelligence' (or cognitive problem-solving) serves to reach goals, but these goals are not defined by it. Organisms may evolve to be highly cooperative regardless of their level of 'intelligence', and vice versa: there are highly altruistic microbes and insects (Tarnita 2017, Wilson 1975), and there are solitary fairly intelligent animals (Mitchell 2016) (in any case sociality, i.e. living in groups, does not imply cooperation, i.e. helping or exchanging resources with others).

It is important here to guard against anthropomorphism, i.e. the notion that everyone is like us and the world can only experienced the way we experience it (Beck 1971, Tipler 1981, Shostak 2010). As stated, 'intelligence' as defined above does not imply cooperation or social living; moreover, whatever one's personal philosophy about morality and what defines 'good' and 'evil', evolution is not it. The motivations of any organisms other than ourselves are thus hard to predict in some ways (Tipler 1980); on the other hand we understand quite well the general goals evolving organisms are adapted to solve (rev. in Krebs and Davies 1993, Todd and Miller 2018). Interestingly, this actually implies that the motivations and goals of any extraterrestrial species may be more aligned with those of living beings on Earth than their physical similarities warrant: they will all care about maximizing reproduction, gathering and defending resources, balancing exploration with exploitation (e.g. Dornhaus 2014, Monk et al. 2018, Garg et al. 2024)[2]. This is exactly why human behaviors like altruism towards non-relatives, information-sharing, and costly exploration are rare, both on and off Earth.

In summary, human-like intelligence is not a single, specific, unique faculty. Instead, it results from a combination of an exceptional degree of behavioral flexibility and abstract thought, with a propensity to live in highly cooperative, large societies. This skillset has enabled the emergence of language as well as a cumulative cultural evolution unparalleled among other organisms on Earth, even if these may show some of these traits in isolation. Language combined with this level of social learning has thus enabled us to benefit from insights (or trial-

[2] Note that these considerations apply to all evolving entities regardless of their origin. Any initially built (by humans or ETIs) 'universal replicators' (Tipler 1980) that truly replicate themselves (rather than producing on an unchanging template) left to their own devices for many generations would also evolve, including acquiring their own 'intentionality' (or selfishness, if one wants to call it that).

and-error learning) achieved generations before and miles away; it is this cultural evolution that makes us who we understand ourselves to be.

The probability of human-like intelligence

To estimate any probability, one usually relates the frequency with which something did happen to the number of chances it had of happening. The frequency of human-like intelligence evolving, to present knowledge, is 1. But how often could it have happened? Was there only one chance (one life, one Earth, assuming, perhaps, that once someone evolves human-like intelligence no other species will get a chance to evolve it)? In that case, it evolved in 100% of cases. This is not terribly informative statistically speaking, however, since we only have one sample. Moreover, if we hadn't evolved this kind of intelligence, we wouldn't be talking about it. If, on the other hand, we assume that each species on Earth could have evolved human-like intelligence (just like many did in fact evolve learning, or navigation based on landmarks, or communication of some kind), then we should conclude that the probability of human-like intelligence evolving is only one in 10 million or so (a similar argument is made in Cabrol 2016; if one wants to calculate a more precise number, it would be necessary to take extinct species into account, and also only count the lineages that are sufficiently distinct to have had independent chances of evolving intelligence; this is however unlikely to give a fundamentally different answer: either way it is a small number that we cannot estimate even to its degree of magnitude, Tipler 1980). Of course the implications of this depend on what species richness we expect on other planets, should they harbor life; what causes species richness is an unsolved, but actively studied, question (Gaston 2000).

Another line of evidence also suggests that human-like intelligence emerges with low probability: it did not appear on Earth for a long time, perhaps only as recently as 50,000 years ago (estimates are typically 250,000 – 50,000 years ago, Sterelny 2016), in East Africa. The human lineage diverged from that of other chimpanzee species around 8 million years ago; hominids started walking upright roughly 4 million years ago, and started using fire and stone tools 2-3 million years ago; the human braincase significantly expanded over the course of the last 2 million years (although note that brain size may be a poor proxy for intelligence, Miller and Penke 2007). But we don't see a truly human degree of innovation, e.g. in the variety of stone tools, or complex social interaction, e.g. in making jewelry or signs of ritual, until about 50

000 (0.05 million) years ago. Anthropologists conclude from this that human language did not appear until that recently, although clearly this is associated with a good measure of uncertainty. This means for (roughly) 99.9987% of Earth's history, life did not evolve human-like intelligence, despite the fact that many species have emerged and disappeared in this time (average species lifespan in mammals is thought to be about 1-10 million years)[3]. This is unlike other, similar traits: communication, for example, is present even in many bacteria (Ben-Jacob et al. 2004) and thus has presumably existed for more than half of Earth's history; navigation skills, i.e. the ability to find the way back to a specific place, is likely as old as animals, roughly 12% of Earth's history (Ma et al. 2012, Budd 2015). This implies that human-like intelligence seems a comparatively recent, and thus low-probability, event.

Why, if this argument is correct, is human-like intelligence so improbable?

Understanding mechanistically when human-like intelligence evolves would allow us to extrapolate to other planets much more effectively than these types of calculations (Cabrol 2016, Gott 1993). Evolutionary biologists constantly develop and test good hypotheses about why particular traits evolve in some species and not others; as discussed above, we do have a considerable body of research about which lifestyles promote the evolution of behavioral flexibility, or spatial memory, or cooperation. Generally, "why"-type explanations for biological traits are derived and tested using modeling (deriving the consequences of different traits given known conditions), empirical measurements (of the success of individuals in which the trait has been manipulated), or comparative studies that identify which conditions, across species, are associated with the trait of interest (Krebs and Davies 1993). Once such explanations are available, we can make predictions about the conditions under which an unknown organism may be thought to evolve a trait. Scientists do not have such explanations for human intelligence. In other words, we do not know why human intelligence (or, in fact, human level cooperation)

---

[3] The Drake equation includes a term of how long intelligent alien civilizations are likely to exist (or at least signal into space). We lack even a single case of human-like intelligence, or life in general, appearing and disappearing, so we have no empirical information on this. People speculate that on Mars life may have existed and disappeared, or that Earth life, or at least human civilization, may disappear due to technological disaster (Gott 1993, Shostak 2010), but both are just that–speculation. Gott (1993), attributing this idea to Darwin, makes the probabilistic assertion that if our contemplation of this question is random with respect to a finite time span, it is on average expected to be in the middle (it is worth noting that probabilities in this case are merely a statement about the status of our knowledge). Non-human-like intelligence on the other hand may, and has, disappeared in any lineage whenever new ecological conditions changed the benefit-cost balance.

evolved. We can trace some of its history, and some of the consequences, but these are not sufficient to deduce *why* this trait evolved. Only a hypothesis from which predictions can be made about the expected level of intelligence in other, as-yet-unstudied, species can count a scientific explanation.

Did human intelligence confer survival benefits for living in the African savannah? Perhaps, but many large mammals live in the savannah, and none of them seem to have evolved anything near human intelligence. In addition, the radical expansion of the human brain, along with the ultimately radically different level of intelligence possessed by humans, did not go along with a corresponding increase in ecological success—early humans did not increase in population size and even may have gone through populations bottlenecks around the same time (Chen and Li 2001). Are primates particularly prone to exploiting the "clever social hunting" niche, thus predisposing only us, not other African mammals, to evolve intelligence? Surely they are, and this is why many primates have comparatively large brains and high intelligence. But no primates other than humans have human-like intelligence, despite the fact that there are many species, including in the African savannah and elsewhere. Another hypothesis revolves around the reproductive benefits gained by individuals with high social intelligence, particularly when living in large groups. Indeed primates in larger groups seem to have a larger cortex (the part of the brain that may be doing the 'thinking'), and thus if humans are the only large primates to evolve larger group sizes, this may explain why only humans became as large-brained as we are (Dunbar 2003). However, there is considerable debate around the evidence for this hypothesis, and more generally, group size or social complexity seems a poor predictor of cognitive evolution (in carnivores: Holekamp et al. 2015, birds: Mitchell 2016, insects: Lihoreau et al. 2012, O'Donnell et al. 2015). Nonetheless, social intelligence in humans is one of our most distinctive traits (Herrmann et al. 2007, Tomasello et al. 1993, Call and Tomasello 2008, Tennie et al. 2009).

There is one remaining hypothesis that by its very nature suggests why human intelligence may be a unique trait: sexual selection (Miller and Todd 1998, Haselton and Miller 2006). Sexual selection refers to a process by which traits may evolve that do not confer survival benefits and in fact may be detrimental to survival. If one or both sexes in a species are choosy about their mates, then any trait that becomes a mate-selection criterion can evolve to unique, exaggerated, and costly (to survival) levels. This process is well-studied in biology (Krebs and

Davies 1993), and for good reason: it is incredibly common–essentially all bird coloring and song is explained by it, as well as extravagant horns, antlers and penis shapes (primarily in insects). It is inherent in this process that the exaggerated trait, such as a peacock's tail, a nightingale's song, or a deer's antlers, is essentially arbitrary: it does not have to have any use other than to impress mating partners or rivals and thus lead to more matings. What if human brains were such a trait? This would explain their fast evolution, distinctness from related species, unclear or absent survival benefits, and rarity as a trait for those same reasons (its arbitrariness and production cost). None of the other hypotheses advanced so far have comparable explanatory power. According to the "Mating Mind" (=human-like intelligence arose by sexual selection) hypothesis (Miller 1993), human-like intelligence is thus essentially an arbitrary trait, only somewhat influenced by the lineage-typical fitness-relevant traits (brains for primates, rather than antlers for deer or feathers for birds). The peacock's tail of primates.

Will Aliens Be Intelligent?

Almost certainly, at least some life forms on other planets, if they exist, will be intelligent in the non-human sense. There are two main arguments for this. First, cognitive skills are frequent on Earth. Even bacteria on Earth show learning, chemotaxis, and social signaling (Shapiro 2007); even insects show tool use, navigation over longer distances including cognitive maps, and many other complex computations (Dornhaus and Franks 2008, Chittka 2023). Many animals show learned and spontaneous problem-solving abilities, and even sessile organisms, like plants, exhibit social interactions and sensory capabilities (Trewavas 2016). All of these skills are so ubiquitous in Earth's organisms that it is hard to imagine aliens "living" without them. Second, we understand something about when cognitive skills evolve: they provide evolutionary benefits exceeding their costs in many ecological conditions. They can provide some robustness to environmental change; they can enable the use of a larger variety of resources and larger home ranges; they enable targeted, short-term behavioral adaptation in a way that is not possible with genetic adaptation. Such behavioral flexibility and robustness to variable environments is likely to be adaptive in any, even an alien, ecosystem. In other words, if intelligence is understood as information processing, cognitive problem solving, or behavioral flexibility, we would predict it to be commonplace wherever life exists. However, we would also predict that its precise form, i.e. the specific cognitive skills present, will depend exactly on the balance of benefits and costs of such skills. However, human-like intelligence appears to be unlikely and rare. No matter the reason, this doesn't bode well for the prospect of finding human-like aliens.

References

Ausmus, Desa M., and Jennifer A. Clarke. 2014. "Mother knows best: Functionally referential alarm calling in white-tailed ptarmigan." *Animal Cognition* 17 (3):671-679. doi: 10.1007/s10071-013-0698-8.

Austin, Matthew W., and Aimee S. Dunlap. "Intraspecific Variation in Worker Body Size Makes North American Bumble Bees (Bombus Spp.) Less Susceptible to Decline." The American Naturalist 194, no. 3 (September 2019): 381–94. https://doi.org/10.1086/704280.

Baluška, František, and Stefano Mancuso. 2009. "Deep evolutionary origins of neurobiology: Turning the essence of 'neural' upside-down." *Communicative & Integrative Biology* 2 (1):60-65.

Barron, Andrew B., and Colin Klein. 2016. "What insects can tell us about the origins of consciousness." *Proceedings of the National Academy of Sciences* 113 (18):4900-4908. doi: 10.1073/pnas.1520084113.

Bayne, Tim, Jakob Hohwy, and Adrian M. Owen. 2016. "Are There Levels of Consciousness?" *Trends in Cognitive Sciences*. doi: http://dx.doi.org/10.1016/j.tics.2016.03.009.

Ben-Jacob, Eshel, Israela Becker, Yoash Shapira, and Herbert Levine. 2004. "Bacterial linguistic communication and social intelligence." *Trends in Microbiology* 12 (8):366-372.

Bernays, Elizabeth. 1999. "Specialists make faster decisions than generalists: experiments with aphids." *Proc. R. Soc. Lond. B* 266:151-156.

Boivin, Nicole L., Melinda A. Zeder, Dorian Q. Fuller, Alison Crowther, Greger Larson, Jon M. Erlandson, Tim Denham, and Michael D. Petraglia. "Ecological Consequences of Human Niche Construction: Examining Long-Term Anthropogenic Shaping of Global Species Distributions." Proceedings of the National Academy of Sciences 113, no. 23 (June 7, 2016): 6388–96. https://doi.org/10.1073/pnas.1525200113.

Boly, Melanie, Anil K Seth, Melanie Wilke, Paul Ingmundson, Bernard Baars, Steven Laureys, David Edelman, and Naotsugu Tsuchiya. 2013. "Consciousness in humans and non-human animals: Recent advances and future directions." *Frontiers in Psychology* 4. doi: 10.3389/fpsyg.2013.00625.

Budd, Graham E. 2015. "Early animal evolution and the origins of nervous systems." *Philosophical Transactions of the Royal Society of London B: Biological Sciences* 370 (1684). doi: 10.1098/rstb.2015.0037.

Call, Josep, and Michael Tomasello. 2008. "Does the chimpanzee have a theory of mind? 30 years later." *Trends in Cognitive Sciences* 12 (5):187-192. doi: http://dx.doi.org/10.1016/j.tics.2008.02.010.

Chen, Feng-Chi, and Wen-Hsiung Li. 2001. "Genomic Divergences between Humans and Other Hominoids and the Effective Population Size of the Common Ancestor of Humans and Chimpanzees." *The American Journal of Human Genetics* 68 (2):444-456. doi: http://dx.doi.org/10.1086/318206.

Chittka, Lars. *The Mind of a Bee*. Princeton University Press, 2023.

Chittka, Lars, and Jeremy Niven. 2009. "Are Bigger Brains Better?" *Current Biology* 19 (21):R995-R1008. doi: http://dx.doi.org/10.1016/j.cub.2009.08.023.

Chittka, Lars, Stephen J. Rossiter, Peter Skorupski, and Chrisantha Fernando. 2012. "What is comparable in comparative cognition?" *Philosophical Transactions of the Royal Society B: Biological Sciences* 367 (1603):2677-2685. doi: 10.1098/rstb.2012.0215.

Cohen, Michael A., and Daniel C. Dennett. "Consciousness Cannot Be Separated from Function." Trends in Cognitive Sciences 15, no. 8 (August 1, 2011): 358–64. https://doi.org/10.1016/j.tics.2011.06.008.Dally, Joanna M., Nathan J. Emery, and Nicola S. Clayton. 2010. "Avian Theory of Mind and counter espionage by food-caching western scrub-jays (Aphelocoma californica)." *European Journal of Developmental Psychology* 7 (1):17-37. doi: 10.1080/17405620802571711.

Day, Rachel L, Kevin N Laland, and F. John Odling-Smee. "Rethinking Adaptation: The Niche-Construction Perspective." *Perspectives in Biology and Medicine* 46, no. 1 (2003): 80–95.

Dennett, Daniel C. 1995. "The unimagined preposterousness of zombies." *Journal of Consciousness Studies* 2 (4):322-26.

Dere, Ekrem, E. Kart-Teke, J. P. Huston, and Maria A. De Souza Silva. 2006. "The case for episodic memory in animals." *Neuroscience & Biobehavioral Reviews* 30 (8):1206-1224. doi: http://dx.doi.org/10.1016/j.neubiorev.2006.09.005.

Diamond, Jared. "Evolution, Consequences and Future of Plant and Animal Domestication." Nature 418, no. 6898 (August 2002): 700–707. https://doi.org/10.1038/nature01019.

Dornhaus A 2014 'Finding food: foraging affects all aspects of an animal's life', in: Yasukawa K 'Animal Behavior, Volume II: Function and Evolution of Animal Behavior', Praeger Publishers

Dornhaus, Anna, and Nigel R. Franks. 2008. "Individual and collective cognition in ants and other insects (Hymenoptera: Formicidae)." *Myrmecological News* 11:215-226.

Dugatkin, Lee Alan. "The Evolution of Cooperation." BioScience 47, no. 6 (1997): 355–62. https://doi.org/10.2307/1313150.

Dukas, Reuven. 2004. "Evolutionary biology of animal cognition." *Annual Review of Ecology Evolution and Systematics* 35:347-374. doi: 10.1146/annurev.ecolsys.35.112202.130152.

Dukas, Reuven. 2008. "Evolutionary Biology of Insect Learning." *Annual Review of Entomology* 53 (1):145-160. doi: doi:10.1146/annurev.ento.53.103106.093343.

Dunbar, Robin. 2003. "Evolution of the Social Brain" *Science* 302:1160-1.

Dunlap, Aimee S., and David W. Stephens. 2009. "Components of change in the evolution of learning and unlearned preference." *Proceedings of the Royal Society of London B: Biological Sciences*. doi: 10.1098/rspb.2009.0602.

Dunlap, Aimee S, Matthew E Nielsen, Anna Dornhaus, and Daniel R Papaj. 2016. "Foraging Bumble Bees Weigh the Reliability of Personal and Social Information." *Current Biology* 26 (9):1195-1199. doi: http://dx.doi.org/10.1016/j.cub.2016.03.009.

Fawcett, Tim W., Benja Fallenstein, Andrew D. Higginson, Alasdair I. Houston, Dave E. W. Mallpress, Pete C. Trimmer, and John M. McNamara. 2014. "The evolution of decision rules in complex environments." *Trends in Cognitive Sciences* 18 (3):153-161. doi: http://dx.doi.org/10.1016/j.tics.2013.12.012.

Fawcett, Tim W., Steven Hamblin, and Luc-Alain Giraldeau. 2013. "Exposing the behavioral gambit: the evolution of learning and decision rules." *Behavioral Ecology* 24 (1):2-11. doi: 10.1093/beheco/ars085.

Franks, Nigel R., James Hooper, Anna Dornhaus, Phillipa J. Aukett, Alexander L. Hayward, and Stefanie Berghoff. 2007. "Reconnaissance and latent learning in ants." *Biology Letters* 274:1505-1509.

Frisch, Karl von. 1967. *The dance language and orientation of bees*. Cambridge: Harvard Univ. Press.

Galea, Liisa A. M., Martin Kavaliers, Klaus-Peter Ossenkopp, D. Innes, and Eric L. Hargreaves. 1994. "Sexually dimorphic spatial learning varies seasonally in two populations of deer mice." *Brain Research* 635 (1–2):18-26. doi: http://dx.doi.org/10.1016/0006-8993(94)91419-2.

Galea, Liisa A. M., and B. S. McEwen. 1999. "Sex and seasonal changes in the rate of cell proliferation in the dentate gyrus of adult wild meadow voles." *Neuroscience* 89 (3):955-964. doi: http://dx.doi.org/10.1016/S0306-4522(98)00345-5.

Gallup, Gordon G., and James R. Anderson. "The 'Olfactory Mirror' and Other Recent Attempts to Demonstrate Self-Recognition in Non-Primate Species." Behavioural Processes 148 (March 1, 2018): 16–19. https://doi.org/10.1016/j.beproc.2017.12.010.

Garg, Ketika, Paul E Smaldino, and Christopher T Kello. "Evolution of Explorative and Exploitative Search Strategies in Collective Foraging." Collective Intelligence 3, no. 1 (January 1, 2024): 26339137241228858. https://doi.org/10.1177/26339137241228858.

Gaston, Kevin J. 2000. "Global patterns in biodiversity." *Nature* 405 (6783):220-227.

Gil, Mariana, Rodrigo J. De Marco, and Randolf Menzel. 2007. "Learning reward expectations in honeybees." *Learning & Memory* 14 (7):491-496.

Gingins, Simon, and Redouan Bshary. 2016. "The cleaner wrasse outperforms other labrids in ecologically relevant contexts, but not in spatial discrimination." *Animal Behaviour* 115:145-155. doi: 10.1016/j.anbehav.2016.02.022.

Giurfa, Martin, Shaowu Zhang, Armin Jenett, Randolf Menzel, and Mandyam V. Srinivasan. 2001. "The concepts of 'sameness' and 'difference' in an insect." *Nature* 410:930-933.

Goodall, Jane. 1964. "Tool-using and aimed throwing in a community of free-living chimpanzees." *Nature* 201:1264-1266.

Gould, James L. 2004. "Animal cognition." *Current Biology* 14:R372-R375.

Greenspan, Ralph J., and Bruno van Swinderen. 2004. "Cognitive consonance: complex brain functions in the fruit fly and its relatives." *Trends in Neurosciences* 27:707-711.

Griffin, Donald R., and Gayle B. Speck. 2004. "New evidence of animal consciousness." *Anim. Cog.* 7:5-18.

Griffiths, Daniel, Anthony Dickinson, and Nicola Clayton. 1999. "Episodic memory: what can animals remember about their past?" *Trends in Cognitive Sciences* 3 (2):74-80. doi: http://dx.doi.org/10.1016/S1364-6613(98)01272-8.

Grim, Tomas. 2006. "The evolution of nestling discrimination by hosts of parasitic birds: why is rejection so rare?" *Evol Ecol Res* 8:785-802.

Haselton, Martie G., and Geoffrey F. Miller. 2006. "Women's fertility across the cycle increases the short-term attractiveness of creative intelligence." *Human Nature* 17 (1):50-73. doi: 10.1007/s12110-006-1020-0.

Hauser, Marc D., Noam Chomsky, and W. Tecumseh Fitch. 2002. "The Faculty of Language: What Is It, Who Has It, and How Did It Evolve?" *Science* 298 (5598):1569-1579. doi: 10.1126/science.298.5598.1569.

Heisenberg, Martin. 2014. "The Beauty of the Network in the Brain and the Origin of the Mind in the Control of Behavior." *Journal of Neurogenetics* 28 (3-4):389-399. doi: 10.3109/01677063.2014.912279.

Herrmann, Esther, Josep Call, María Victoria Hernàndez-Lloreda, Brian Hare, and Michael Tomasello. 2007. "Humans Have Evolved Specialized Skills of Social Cognition: The Cultural Intelligence Hypothesis." *Science* 317 (5843):1360-1366. doi: 10.1126/science.1146282.

Holekamp, Kay E., Ben Dantzer, Gregory Stricker, Kathryn C. Shaw Yoshida, and Sarah Benson-Amram. 2015. "Brains, brawn and sociality: a hyaena's tale." *Animal Behaviour* 103:237-248. doi: 10.1016/j.anbehav.2015.01.023.

J. Rankin, Daniel, and Andrés López-Sepulcre. 2005. "Can adaptation lead to extinction?" *Oikos* 111 (3):616-619. doi: 10.1111/j.1600-0706.2005.14541.x.

Janik, Vincent M. 2013. "Cognitive skills in bottlenose dolphin communication." *Trends in Cognitive Sciences* 17 (4):157-159. doi: http://dx.doi.org/10.1016/j.tics.2013.02.005.

Johnston, Timothy D. 1982. "Selective Costs and Benefits in the Evolution of Learning." In *Advances in the Study of Behavior*, edited by Robert A. Hinde Colin Beer Jay S. Rosenblatt and Busnel Marie-Claire, 65-106. Academic Press.

Kerr, Benjamin, and Marcus W. Feldman. 2003. "Carving the Cognitive Niche: Optimal Learning Strategies in Homogeneous and Heterogeneous Environments." *Journal of Theoretical Biology* 220 (2):169-188. doi: http://dx.doi.org/10.1006/jtbi.2003.3146.

Kilner, Rebecca M., and Naomi E. Langmore. 2011. "Cuckoos versus hosts in insects and birds: adaptations, counter-adaptations and outcomes." *Biological Reviews* 86 (4):836-852. doi: 10.1111/j.1469-185X.2010.00173.x.

Koops, Kathelijne, Elisabetta Visalberghi, and Carel P. van Schaik. 2014. "The ecology of primate material culture." *Biology Letters* 10 (11):4. doi: 10.1098/rsbl.2014.0508.

Kramer, Karen L. "Cooperative Breeding and Its Significance to the Demographic Success of Humans." Annual Review of Anthropology 39, no. Volume 39, 2010 (October 21, 2010): 417–36. https://doi.org/10.1146/annurev.anthro.012809.105054.

Krebs, John B., and Nicholas B. Davies. 1993. *An introduction to behavioural ecology*: Blackwell Scientific Publications.

Krützen, Michael, Janet Mann, Michael R. Heithaus, Richard C. Connor, Lars Bejder, and William B. Sherwin. 2005. "Cultural transmission of tool use in bottlenose dolphins." *Proceedings of the National Academy of Sciences of the United States of America* 102 (25):8939-8943.

Latham, Roger Earl, and Robert E. Ricklefs. 1993. "Global Patterns of Tree Species Richness in Moist Forests: Energy-Diversity Theory Does Not Account for Variation in Species Richness." *Oikos* 67 (2):325-333. doi: 10.2307/3545479.

Laverty, Terence M., and R C. Plowright. 1988. "Flower handling by bumblebees: a comparison of specialists and generalists." *Anim. Behav.* 36:733-740.

Leadbeater, Ellie, and Lars Chittka. 2007. "Social learning in insects - From miniature brains to consensus building." *Current Biology* 17 (16):R703-R713.

Lihoreau, Mathieu, Tanya Latty, and Lars Chittka. 2012. "An Exploration of the Social Brain Hypothesis in Insects." *Frontiers in Physiology* 3:442. doi: 10.3389/fphys.2012.00442.

Lindley, Craig A. 2013. "Neurobiological Computation and Synthetic Intelligence." In *Computing Nature: Turing Centenary Perspective*, edited by Gordana Dodig-Crnkovic and Raffaela Giovagnoli, 71-85. Berlin, Heidelberg: Springer Berlin Heidelberg.

Liu, Li, Reinhard Wolf, Roman Ernst, and Martin Heisenberg. 1999. "Context generalization in *Drosophila* visual learning requires the mushroom bodies." *Nature* 400:753-756.

Liu, Yuxiang X., Lainy B. Day, Kyle Summers, and Sabrina S. Burmeister. 2016. "Learning to learn: advanced behavioural flexibility in a poison frog." *Animal Behaviour* 111:167-172. doi: 10.1016/j.anbehav.2015.10.018.

Ma, Xiaoya, Xianguang Hou, Gregory D. Edgecombe, and Nicholas J. Strausfeld. 2012. "Complex brain and optic lobes in an early Cambrian arthropod." *Nature* 490 (7419):258-261. doi: http://www.nature.com/nature/journal/v490/n7419/abs/nature11495.html#supplementary-information.

Marshall, James A. R., Rafal Bogacz, Aanna Dornhaus, Robert Planque, Tim Kovacs, and Nigel R. Franks. 2009. "On optimal decision-making in brains and social insect colonies." *Journal of the Royal Society Interface* 6:1065-1074.

Mashour, George A., and Michael T. Alkire. 2013. "Evolution of consciousness: Phylogeny, ontogeny, and emergence from general anesthesia." *Proceedings of the National Academy of Sciences* 110 (Supplement 2):10357-10364. doi: 10.1073/pnas.1301188110.

Matzel, Louis D., and Stefan Kolata. 2010. "Selective attention, working memory, and animal intelligence." *Neuroscience & Biobehavioral Reviews* 34 (1):23-30. doi: http://dx.doi.org/10.1016/j.neubiorev.2009.07.002.

McIntosh, Margrit E. 2005. "Pollination of two species of Ferocactus: interactions between cactus-specialist bees and their host plants." *Functional Ecology* 19 (4):727-734. doi: 10.1111/j.1365-2435.2005.00990.x.

Menzel, Randolf, Rebecca Brandt, Andreas Gumbert, Bernhard Komischke, and Jan Kunze. 2000. "Two spatial memories for honeybee navigation." *Proceedings of the Royal Society of London B: Biological Sciences* 267 (1447):961-968. doi: 10.1098/rspb.2000.1097.

Menzel, Randolf, and Martin Giurfa. 2001. "Cognitive architecture of a mini-brain: the honeybee." *Trends in Cognitive Sciences* 5:62-71.

Mesoudi, Alex. “Cultural Evolution: A Review of Theory, Findings and Controversies.” Evolutionary Biology 43, no. 4 (December 1, 2016): 481–97. https://doi.org/10.1007/s11692-015-9320-0.

Mery, Frederic, and Tadeusz J. Kawecki. 2003. "A fitness cost of learning ability in Drosophila melanogaster." *Proc Roy Soc B* 270:2465-2469.

Mery, Frederic, and Tadeusz J. Kawecki. 2004. "An operating cost of learning in Drosophila melanogaster." *Anim. Behav.* 68:589-598.

Michalet, Richard, Robin W. Brooker, Lohengrin A. Cavieres, Zaal Kikvidze, Christopher J. Lortie, Francisco I. Pugnaire, Alfonso Valiente-Banuet, and Ragan M. Callaway. 2006. "Do biotic interactions shape both sides of the humped-back model of species richness in plant communities?" *Ecology Letters* 9 (7):767-773. doi: 10.1111/j.1461-0248.2006.00935.x.

Miller, Geoffrey F., and Lars Penke. 2007. "The evolution of human intelligence and the coefficient of additive genetic variance in human brain size." *Intelligence* 35 (2):97-114. doi: http://dx.doi.org/10.1016/j.intell.2006.08.008.

Miller, Geoffrey F., and Peter M. Todd. 1998. "Mate choice turns cognitive." *Trends in Cognitive Sciences* 2 (5):190-198. doi: http://dx.doi.org/10.1016/S1364-6613(98)01169-3.

Miller, Geoffrey Franklin. 1993. "Evolution of the human brain through runaway sexual selection the mind as a protean courtship device."

Mitchell, Christopher. "The Evolution of Brains and Cognitive Abilities." In Evolutionary Biology: Convergent Evolution, Evolution of Complex Traits, Concepts and Methods, edited by Pierre Pontarotti, 73–87. Cham: Springer International Publishing, 2016. https://doi.org/10.1007/978-3-319-41324-2_5.

Mix, Lucas John. 2014. "Defending Definitions of Life." *Astrobiology* 15 (1):15-19. doi: 10.1089/ast.2014.1191.

Monk, Christopher T., Matthieu Barbier, Pawel Romanczuk, James R. Watson, Josep Alós, Shinnosuke Nakayama, Daniel I. Rubenstein, Simon A. Levin, and Robert Arlinghaus. "How Ecology Shapes Exploitation: A Framework to Predict the Behavioural Response of Human and Animal Foragers along Exploration–Exploitation Trade-Offs." Ecology Letters 21, no. 6 (2018): 779–93. https://doi.org/10.1111/ele.12949.

Morrill, Wendell L. 1972. "Tool using behavior of Pogonomyrmex badius (Hymenoptera: Formicidae)." *The Florida Entomologist* 55:59-60.

Muth, Felicity, Tamar Keasar, and Anna Dornhaus. 2015. "Trading off short-term costs for long-term gains: how do bumblebees decide to learn morphologically complex flowers?" *Animal Behaviour* 101:191-199. doi: http://dx.doi.org/10.1016/j.anbehav.2014.12.024.

Nagel, Thomas. “What Is It Like to Be a Bat?” The Philosophical Review 83, no. 4 (1974): 435–50. https://doi.org/10.2307/2183914.

Navarrete, Ana F., Simon M. Reader, Sally E. Street, Andrew Whalen, and Kevin N. Laland. 2016. "The coevolution of innovation and technical intelligence in primates." *Philosophical Transactions of the Royal Society B-Biological Sciences* 371 (1690):10. doi: 10.1098/rstb.2015.0186.

Northoff, Georg, and Victor Lamme. “Neural Signs and Mechanisms of Consciousness: Is There a Potential Convergence of Theories of Consciousness in Sight?” Neuroscience & Biobehavioral Reviews 118 (November 1, 2020): 568–87. https://doi.org/10.1016/j.neubiorev.2020.07.019.

O'Donnell, Sean, Susan J. Bulova, Sara DeLeon, Paulina Khodak, Skye Miller, and Elisabeth Sulger. 2015. "Distributed cognition and social brains: reductions in mushroom body investment accompanied the origins of sociality in wasps (Hymenoptera: Vespidae)." *Proceedings of the Royal Society B-Biological Sciences* 282 (1810):6. doi: 10.1098/rspb.2015.0791.

Odling-Smee, Lucy C., Janette W. Boughman, and Victoria A. Braithwaite. 2008. "Sympatric species of threespine stickleback differ in their performance in a spatial learning task." *Behavioral Ecology and Sociobiology* 62 (12):1935-1945. doi: 10.1007/s00265-008-0625-1.

Penn, Derek C, and Daniel J Povinelli. 2007. "On the lack of evidence that non-human animals possess anything remotely resembling a ‘theory of mind’." *Philosophical Transactions of the Royal Society B: Biological Sciences* 362 (1480):731-744. doi: 10.1098/rstb.2006.2023.

Pereda, María, Débora Zurro, José I. Santos, Ivan Briz i Godino, Myrian Álvarez, Jorge Caro, and José M. Galán. “Emergence and Evolution of Cooperation Under Resource Pressure.” Scientific Reports 7, no. 1 (March 31, 2017): 45574. https://doi.org/10.1038/srep45574.

Peterson, A. Town, Jorge Soberón, and Victor Sánchez-Cordero. 1999. "Conservatism of Ecological Niches in Evolutionary Time." *Science* 285 (5431):1265-1267. doi: 10.1126/science.285.5431.1265.

Raine, Nigel E., and Lars Chittka. 2006. "Pollen foraging: learning a complex motor skill by bumblebees (Bombus terrestris)." *Naturwissenschaften* 94 (6):459-464. doi: 10.1007/s00114-006-0184-0.

Reid, Chris R., Tanya Latty, Audrey Dussutour, and Madeleine Beekman. 2012. "Slime mold uses an externalized spatial “memory” to navigate in complex environments." *Proceedings of the National Academy of Sciences of the United States of America* 109 (43):17490-17494. doi: 10.1073/pnas.1215037109.

Richardson, Tom O., P.A. Sleeman, John M. McNamara, Alasdair I. Houston, and Nigel R. Franks. 2007. "Teaching with evaluation in ants." *Current Biology* 17 (17):1520-1526.

Roth, Gerhard, and Ursula Dicke. 2005. "Evolution of the brain and intelligence." *Trends in Cognitive Sciences* 9 (5):250-257. doi: 10.1016/j.tics.2005.03.005.

Sayers, Ken, Theodore A. Evans, Emilie Menzel, J. David Smith, and Michael J. Beran. 2015. "The misbehaviour of a metacognitive monkey." *Behaviour* 152 (6):727-756. doi: 10.1163/1568539x-00003251.

Seyfarth, Robert M., Dorothy L. Cheney, and Peter Marler. 1980. "Vervet monkey alarm calls: Semantic communication in a free-ranging primate." *Animal Behaviour* 28 (4):1070-1094. doi: http://dx.doi.org/10.1016/S0003-3472(80)80097-2.

Shapiro, James A. 2007. "Bacteria are small but not stupid: cognition, natural genetic engineering and socio-bacteriology." *Studies in History and Philosophy of Science Part C: Studies in History and Philosophy of Biological and Biomedical Sciences* 38 (4):807-819. doi: http://dx.doi.org/10.1016/j.shpsc.2007.09.010.

Sherry, David F., Lucia F. Jacobs, and Steven J. C. Gaulin. 1992. "Spatial memory and adaptive specialization of the hippocampus." *Trends in Neurosciences* 15 (8):298-303. doi: http://dx.doi.org/10.1016/0166-2236(92)90080-R.

Shettleworth, Sara. 1998. *Cognition, Evolution, and the Study of Behavior*: Oxford University Press.

Shettleworth, Sara .J., John R. Krebs, David W. Stephens, and John Gibbon. 1988. "Tracking a fluctuating environment: a study of sampling." *Anim. Behav.* 36:87-105.

Shettleworth, Sara J. 2010. "Clever animals and killjoy explanations in comparative psychology." *Trends in Cognitive Sciences* 14 (11):477-481. doi: 10.1016/j.tics.2010.07.002.

Slobodchikoff, Constantine N., Judith Kiriazis, C. Fischer, and E. Creef. 1991. "Semantic information distinguishing individual predators in the alarm calls of Gunnison's prairie dogs." *Animal Behaviour* 42 (5):713-719. doi: http://dx.doi.org/10.1016/S0003-3472(05)80117-4.

Smaldino, Paul E., and Jeffrey C. Schank. "Movement Patterns, Social Dynamics, and the Evolution of Cooperation." Theoretical Population Biology 82, no. 1 (August 1, 2012): 48–58. https://doi.org/10.1016/j.tpb.2012.03.004.

Stephens, David W. 1991. "Change, regularity, and value in the evolution of animal learning." *Behavioral Ecology* 2 (1):77-89. doi: 10.1093/beheco/2.1.77.

Sterelny, Kim. 2016. "Adaptable individuals and innovative lineages." *Philosophical Transactions of the Royal Society of London B: Biological Sciences* 371 (1690). doi: 10.1098/rstb.2015.0196.

Tarnita, Corina E. "The Ecology and Evolution of Social Behavior in Microbes." Edited by Joel D. Levine, Daniel J. C. Kronauer, and Michael H. Dickinson. Journal of Experimental Biology 220, no. 1 (January 1, 2017): 18–24. https://doi.org/10.1242/jeb.145631.

Tarsitano, Michael S., and Robert R. Jackson. 1997. "Araneophagic jumping spiders discriminate between detour routes that do and do not lead to prey." *Animal Behaviour* 53:257-266.

Tennie, Claudio, Josep Call, and Michael Tomasello. "Ratcheting up the Ratchet: On the Evolution of Cumulative Culture." Philosophical Transactions of the Royal Society B: Biological Sciences 364, no. 1528 (August 27, 2009): 2405–15. https://doi.org/10.1098/rstb.2009.0052.

Tibbetts, Elizabeth. A. 2002. "Visual signals of individual identity in the wasp Polistes fuscatus." *Proc Roy Soc B* 269:1423-1428.

Todd, Peter M., and Geoffrey F. Miller. "The Evolutionary Psychology of Extraterrestrial Intelligence: Are There Universal Adaptations in Search, Aversion, and Signaling?" Biological Theory 13, no. 2 (June 1, 2018): 131–41. https://doi.org/10.1007/s13752-017-0290-6.

Tomasello, Michael, Ann Cale Kruger, and Hillary Horn Ratner. 1993. "Cultural Learning." *Behavioral and Brain Sciences* 16 (3):495-511.

Trewavas, Anthony. 2016. "Intelligence, cognition and language of green plants." *Frontiers in Psychology* 7. doi: 10.3389/fpsyg.2016.00588.

Trewavas, Anthony J, and František Baluška. 2011. "The ubiquity of consciousness." *The ubiquity of consciousness, cognition and intelligence in life* 12 (12):1221-1225. doi: 10.1038/embor.2011.218.

Van Valkenburgh, Blaire, Xiaoming Wang, and John Damuth. 2004. "Cope's Rule, Hypercarnivory, and Extinction in North American Canids." *Science* 306 (5693):101-104. doi: 10.1126/science.1102417.

Wehner, Ruediger. 1971. "The generalization of directional visual stimuli in the honey bee, Apis mellifera." *J. Insect Physiol.* 17:1579-1591.

Weir, Alex A. S., Jackie Chappell, and Alex Kacelnik. 2002. "Shaping of Hooks in New Caledonian Crows." *Science* 297 (5583):981-981. doi: 10.1126/science.1073433.

Wilson, Edward O. Sociobiology: The New Synthesis. Sociobiology: The New Synthesis. Oxford, England: Belknap Press of Harvard U Press, 1975.

Zhang, Shaowu, Fiola Bock, Aung Si, Juergen Tautz, and Mandyam V. Srinivasan. 2005. "Visual working memory in decision making by honey bees." *Proceedings of the National Academy of Sciences of the United States of America* 102 (14):5250-5255. doi: 10.1073/pnas.0501440102.