The ubiquity of consciousness

The ubiquity of consciousness, cognition and intelligence in life

Anthony J. Trewavas & František Baluška

In his essay, *What about 'information'?*, Massimo Pigliucci (2011) makes an eloquent argument to counter the claims of supporters of intelligent design, who argue that the evolution of intelligence must have been guided by some supernatural force. But, in making his case, he states that “only humans and other relevantly similar conscious organisms have knowledge”. He is certainly not the only one who considers that ‘knowledge’ and consciousness are qualities unique to highly developed species such as humans, dolphins or higher apes, denying them to the vast majority of species and organisms on Earth.

“In the simplest sense, consciousness is an awareness [...] of the outside world”

However, many definitions of consciousness and intelligence are inevitably anthropocentric and therefore hamper our efforts to see these qualities in other species. Lynn Margulis, author of the endosymbiotic theory of organelle evolution, provides a more inclusive definition of consciousness and intelligence: “Not just animals are conscious but every organized being is conscious. In the simplest sense, consciousness is an awareness (has knowledge) of the outside world” (Margulis & Sagan, 1995). Similarly, the Chilean biologist and philosopher Humberto Maturana wrote that “Living systems are cognitive systems and living as a process is a process of cognition. This statement is valid for all organisms with and without a nervous system” (Maturana, 1970). Cognition here refers to the behaviour of any living system in relation to its environment. These debates still reflect common attitudes of the early twentieth century that regarded

most organisms as mechanistic—even mechanical—systems that blindly follow predetermined programmes of behaviour supposedly inscribed in their genes. Modern views instead emphasize plasticity in development and behaviour that counter these mechanistic misunderstandings.

Donald Griffin (1915–2003), who spent his career researching animal behaviour, was the most cogent and early critic of anthropocentric definitions of intelligence and consciousness. Consciousness in any other organism cannot be directly ascertained, he maintained, because of our inability to communicate, to ask relevant questions. But failure to communicate does not mean the absence of any capability; instead, we need to analyse the types of communication of which organisms are capable. In fact, on what experimental evidence, other than supposition, do we reject consciousness in other organisms?

Awareness (consciousness) confers a significant adaptive advantage that enables organisms to react appropriately to physical, biological and social signals from their environment. Mechanistic beliefs assume that behaviour is simple and most organisms merely show reflexes. This attitude is the result of experimental investigations that force organisms to behave in particular ways and have led to erroneous conclusions about the behaviour of organisms in their natural environments. Griffin, by contrast, adamantly denied such mechanistic attitudes. “The crippling limitations of such intellectual myopia should be clearly apparent; the simplicity lies not in the behaviour but in its description,” he wrote (Griffin, 1976). This view is echoed by Kevin Warwick, a British scientist working on artificial intelligence: “I believe that dogs

and cats are conscious in their own way, and bees, ants and spiders are conscious, not as humans but as bees, ants and spiders. I cannot say that a robot with a computer for a brain is not conscious because its brain is not like mine and because it thinks in a different way to me” (Warwick, 2000).

Only ‘wild’ behaviour in the natural environment is really meaningful for observing conscious, intelligent behaviour

More generally, we regard intelligent behaviour as the capacity for solving problems and consider it to be inextricably linked to evolutionary fitness. The German biochemist and Nobel laureate Manfred Eigen, provides definitions of learning, memory and intelligence at the molecular level that suggest how organisms might have evolved such behaviours (Eigen & de Maeyer, 1966). Clearly, not every behavioural trait is a sign of intelligence, but when the environment is unpredictable in terms of food resources or the presence of predators, innate behaviour is maladaptive and threatens survival. Fitness favours those organisms that can adapt.

The ability to learn from experience and adapt behaviour accordingly is most apparent among the higher vertebrates. Teaching a chimpanzee 300 words using sign language or observing that chimps stack boxes to reach a hanging banana are indeed impressive, but these are still experimental designs that impose human criteria of consciousness and intelligence. Chimpanzees can take hours, days or months to learn how to solve some laboratory problems, but they need only seconds to learn a particular dominance status when they encounter a new social situation. Only ‘wild’ behaviour in the

natural environment is really meaningful for observing conscious, intelligent behaviour.

Until now, the research animal most endowed with human qualities was a grey parrot named Alex, trained by Irene Pepperberg and her collaborators (http://www.alexfoundation.org/alex_the_parrot.html). Alex had a spoken language of about 100 words, understood abstract terms, such as shape—smaller, larger, same, different—could count to six, and could identify many colours. He learnt to ask for things and would reject them if they were not what he wanted. He had a remarkable understanding of the properties of particular objects and could identify the materials from which they were made. He could assess the properties of new objects even if he had not seen the specific combination of materials before. Most remarkably, he could apologize if he annoyed his trainer. Alex was clearly conscious and intelligent. Birds and mammals evolved from evolutionary branches that separated several hundred million years ago. Thus intelligent behaviour in these organisms has arisen separately, a portent for potential intelligent behaviour in other organisms.

Corvids—ravens, crows or jays—also exhibit intelligent behaviour within their natural environment (Heinrich & Bungnyar, 2007; Seed *et al.*, 2008). Seed caching is common among corvids and indicates foresight. Jays can remember the precise position of thousands of seeds through cognitive maps that they construct when they hide their stash. If competitors observe them preparing their cache, they will move it privately later, but only if they themselves have previously pilfered another bird's seed cache. When presented with food hanging from the end of a long string attached to their perch, ravens solve the problem by drawing up the food using beak and claw after a few minutes thought and without any trial and error. This is a clear case of abstract thinking. Different ravens come up with a variety of solutions to this simple puzzle. If one raven finds the food too heavy, it will recruit a mate for help and the speed of recruitment is determined by the closeness of the relationship between the two. Crows use sticks to probe holes for insects. Given a choice, they immediately select the stick with the right diameter for the appropriate hole. When presented with food at the bottom of a tube too deep to reach with the beak, one crow has been observed to bend a piece of wire into a hook to pull up the food. In experimental situations, crows will

follow the direction of the experimentalist's gaze. Ravens have also been seen to console other distressed ravens. These birds clearly show self-awareness, intelligence and consciousness. Abilities have to be judged not on the details of behaviour—by use of beak and claw, rather than opposable thumbs—but on whether the problem is solved, by whatever the means. To assume otherwise is to judge subjectively (Warwick, 2000).

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The fact that intelligent behaviour is apparent in higher apes, corvids and parrots suggests that social interactions might be a prerequisite for consciousness and intelligence. All these animals live in groups or flocks, so social interaction is inevitable. Similarly, human intelligence evolved among our ancestors through the positive feedback implicit in social interactions. But there are many other organisms, including micro-organisms, that have adopted social lifestyles—indeed multicellular organisms can be regarded as colonies of socially interacting cells—and that could benefit from intelligent behaviour through social interaction.

The most thoroughly investigated of the social ‘lower’ life forms are ants and bees. Their self-organizing interactions construct an emergent ‘swarm intelligence’. “It is not too much to say that a bee colony is capable of cognition in much the same sense that a human being is. The colony gathers and continually updates diverse information about its surroundings, combines this with information about its internal state and makes decisions that reconcile its well being with its environment” (Seeley & Levien, 1987). Is the colony—or the ‘super-organism’ it represents—both intelligent and conscious? Can one exist without the other?

As all biological systems—including insect colonies—are networks with varying degrees of complexity, the question is rather whether such swarm intelligence networks are too simple to express more sophisticated ‘intelligence’? Detailed examination of individual insect behaviour suggests that neither colonies nor insects are simple systems (Griffin, 1976). The physical and acoustic ‘dance’ performed by a returning bee conveys detailed knowledge and integrates information from

both outside and inside the hive. There is evidence that a few leaders then recruit worker bees that have seen the dance to the new origin of food, while many other workers who also saw the dance continue with their previous tasks. In a similar fashion, experienced foraging ants lead naive nest mates in the right direction to food or a new nest site. This “was the first case in which teaching, as strictly defined, was shown in a non-human animal” (Franks & Richardson, 2006).

Usually, a few scouts—ants and bees—investigate new nest sites, assess the level of suitability and convey that information quantitatively to others. Ant scouts actually measure the internal size of a new nest and assess the suitability of possible entrances. They further examine the new site until a ‘quorum of approval’ results in a decision to move, led, of course, by scouts. Poor sites take longer for approval. What constitutes the threshold for approval and the subsequent move is not understood.

Individual bees process information using spatial and counting memories and can recognize images of complex natural scenes with very fine discrimination. Experimental investigations show that bees exhibit associative recall; categorize and interpolate visual information; master abstract relationships such as sameness and difference; group together similarly shaped objects; and learn contextual information (Giurfa *et al.*, 2001; Gross *et al.*, 2009). Bees can generalize simple learning exercises and adapt them to new situations; they can learn to fly through mazes via spatial landmarks, transferring that memory of marks to new mazes, and using landmarks and landscape structure to estimate distance and hive position. Alternatively, if trained at a specific time of day with an orientation cue, they can recall this information to navigate new mazes in the absence of orientation information. “A bee knows what to do, when and also where” (Pahl *et al.*, 2007). They can subitize, that is, assess at a glance a quantity of items up to four (Gross *et al.*, 2009)—note that the limit for humans is between four and seven. Individual bees were trained to extend their proboscis into a drop of sugar solution when it was offered. By providing the drop at defined intervals, each bee rapidly learnt to predict when the next drop would appear and extended its proboscis in anticipation. Thus bees have a sense of the future and a memory of the past. Bees can also prioritize flower visits and optimize

costs (flying time) against benefits (nectar yields). After training, bees can discriminate bilateral symmetry from non-symmetrical patterns, transfer the experience to other situations and recognize bilateral axis rotation. Finally, ants and bees can choose to make a trade-off between speed and accuracy. They also acquire long-term memories of past experience because frequent movement to different sites progressively reduces the total move time.

Are these organisms self-aware? Ants do not attack other nest mates but will attack other nests of the same species. Bees will attack hive intruders including other genotypes and recruit others to the attack by means of pheromones. All of this demonstrates perception and awareness of self, compared with other bee genotypes and non-nest members.

Even 'simpler' organisms show signs of self-awareness. Species of the sea anemone *Actinaria* often reproduce through cloning; if two clones contact each other, they fight to establish supremacy leaving a distinctive anemone-free zone between them. Clone colonies contain 'warrior' polyps along the borders and larger reproductive types deeper in the colony with five intergrading castes.

“It is puzzling that primitive organisms that lack any kind of nervous system show sophisticated behaviours that we assume require a nervous system. Many examples noted in the past belie this assumption” (Bonner, 2010). This statement introduced experimental observations of the slime mould *Physarum* that demonstrated its ability to discriminate between a great variety of food sources and to explore only those that provide the optimal diet for growth. *Physarum* can also navigate a maze to connect the shortest distance between food and its present position; some argue that such properties indicate a primitive intelligence (Nakagaki *et al*, 2000). By using minimal path length and optimal tube thickness, *Physarum* minimizes energy expenditure for maximal energy gain. When subjected to shocks at periodic intervals, *Physarum* remembers the frequency and is able to predict the appearance of the next one “hinting at the origin of intelligence” (Ball, 2008). When required to behave more quickly, the slime mould makes more mistakes, which indicates trade-offs between speed and accuracy.

Such apparent signs of learning and consideration are not confined to slime moulds and other primitive multicellular organisms,

but can also be observed in protozoans. When *Paramecia* are confined to tubes smaller in diameter than the length of the protozoan, they initially require a few minutes to turn; with some practice, the cells become capable of turning in a few seconds—an observation that indicates learning in a single-cell protozoan. In a study in the 1920s, other protozoans including *Stentor*, *Didinium* and *Amoeba* showed a surprising variety of behaviours (Jennings, 1923), leading the author to conclude that because their behaviour could be modified by experience, it was surely a sign of intelligence. Moreover, as this learning behaviour was objectively similar to that of mankind, Jennings suggested that consciousness is distributed throughout the animal kingdom. Some amoebae and other protists build protective and elaborate enveloping cases (houses) from gathered material. This and other observations on the behaviour of

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Amoeba led Walker (2005) to conclude that “*Amoeba* perceives, recognizes, chooses and ingests a variety of prey that is not much short of the choice of higher animals, it recognizes its own kind and engages in cooperative behaviour,” particularly in cooperative hunting. Recognition of its own kind would indicate that amoebae are self-aware.

So, what about bacteria, the simplest of all cells? Four aspects of bacterial behaviour have received much attention so far: chemotaxis, signal transduction, quorum sensing and the formation of large morphologies. Bacterial signal transduction—more than 50 signals have so far been identified—is controlled by a phosphoneural network in which changes in phosphorylation create or break network connections, thereby acting as logical operators (Hellingwerf, 2005). This process is analogous to changes in dendritic connections in the brain and it enables bacteria to make ‘informed decisions’. Autoamplification of parts of the network in response to environmental signals results in ‘learning behaviour’ (Hellingwerf, 2005). “Some of the most basic properties of brains such as sensory integration, memory, decision-making and the control of behaviour can all be found in these simple organisms” (Allmann, 1999).

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Bacteria also communicate with each other in a variety of ways. Biofilm formation and quorum sensing lead to changes in bacterial behaviour when a quorum is reached, similarly to the behaviour of social insects. Self-identity and social recognition—that is, awareness of members of their own species—has also been observed (Gibbs *et al.*, 2008). Under conditions of starvation or on hard surfaces, bacterial populations self-organize into highly structured morphologies that are thought to represent survival strategies. These morphologies can originate from travelling waves of motile bacteria that enable individual cells to find appropriate environments. The structured colony is capable of collective sensing and communication through large or small molecules, distributed information processing and collective gene regulation; these are yet more examples of cognitive functions and social intelligence.

The bacterial cell can therefore no longer be regarded as a simple, self-contained bag of enzymes supposedly less complex than eukaryotes. Instead, bacteria anticipate predictable changes in their environment with a clear sense of both time and space and their immediate neighbours. They also modify their living space to their own advantage.

At what level of complexity and communication do networks become conscious? Any network able to control its own behaviour by changing connection strengths, storing acquired information, redirecting information flow and recognizing its own kind compared with others would fit the necessary criteria; the obvious analogy between bacterial behaviour with swarm intelligence underpins the notion that the collective behaviour of bacterial colonies shows signs of both consciousness and intelligence.

Finally, can we also observe consciousness, self-awareness and intelligence among plants? This is more challenging because experimental observations of plant behaviour are hampered by various factors: higher plants develop on a much slower timescale than most animals; the experience of most scientists and the public is with domesticated plants in laboratory or garden environments, whereas intelligent behaviour requires observations in the wild; a crucial part of plant behaviour takes place below ground.

To address plant intelligence, we therefore have to look at plants in their natural environments where they need to maximize the acquisition of patchily distributed resources, deny them to competitors and minimize predation and disease because seed number and thus fitness is determined by accumulated reserves. Went & Thimann (1937) concluded that “in tropic movements (to light and gravity) plants appear to exhibit a kind of intelligence; their movement is of subsequent advantage to them” indicating fitness criteria for intelligence. Went was the discoverer of auxin, a crucial plant hormone. Fitness also includes a choice of partners: “There is good evidence that plants can choose their mating partners—they just do it differently from animals” (Moore & Pannell, 2010).

Generally, plants are constructed from populations of competing and cooperating meristems. Individual meristems sense and pursue resource gradients and forage by proliferating local meristems into rich resource patches, thereby adapting the phenotype. But the overall behaviour of an individual

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plant is much more integrated and coordinated to optimize fitness. The cambium in the shoot, a meristematic inner skin, continually assesses and integrates the productive behaviour of all shoot branches. The pericycle and cambium fulfil a similar function in the root. The plant generates vascular tissue to supply shoot branches with more root resources that are predicted to be more productive in terms of carbohydrate production and other leaf functions (Novoplansky, 2003), whereas less productive branches lose vascular elements—this strategy is crucial in the plants’ competition for light. Another sensory mechanism measures the distance to the shoots of competitors so the plant can take predictive actions by outgrowing the competition before experiencing any loss of photosynthetic yield.

“To paraphrase Seeley and Levien (1987), it is not too much to say that a plant is capable of cognition in the same way that a human being is. The plant gathers and continually updates diverse information about its surroundings, combines this with internal information about its internal state and makes decisions that reconcile its well-being with the environment” (Trewavas, 2009). Again, there are analogies in behaviour between social insect colonies (swarm intelligence) and higher plant behaviour.

At least 20 biological, physical, chemical and electrical plant signals that lead to phenotypic changes have been identified with discrimination on the length, direction and intensity of the signal. Most signals induce a memory that can last, depending on the signal, for hours or days, or even up to years in the case of ‘priming’ against pest resistance. Once learnt, these memories usually ensure a much quicker and more forceful response to subsequent signalling (Trewavas, 2009). Through crosstalk, some memories become associative, inducing specific cellular changes. If one plant is attacked by insects, for example, it releases specifically synthesized volatiles that are sensed by other local plants, which then initiate the synthesis of defence mechanisms to pre-empt attack (Dicke, 2009).

Parasitic plants sense their potential host through released volatiles and capture their

prey by following the scent gradient. In the first few hours of contact, the parasite makes an assessment of the future resources that can be gained from the host. If these are insufficient, contact is severed. If the resources are sufficient for exploitation, the parasite calculates the minimal energy outlay to ensure maximal energy gain and specifies the extent to which it needs to develop its haustoria—the resource-acquiring structures. Thus, parasitic plants optimally forage their host in accordance with the marginal value model of animal feeding. Carnivorous plants also show choice over their ‘prey’, as do climbing plants that discriminate between the characteristics of their supporting material.

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There are many more signals, the identity of which remain to be uncovered. The growing roots of an individual plant spread apart in the soil on the basis of a strategy of self-inhibition. The plant uses sensing mechanisms to construct a spatial map of the local soil and identify inanimate objects, directing growth away before contact (Falik *et al*, 2005). Detection of competitive, genotypically related individuals locally in the soil leads to an increase and redirection of root proliferation away from the competitor, often leaving a band of unoccupied soil between them: brethren will not occupy the other individual's territory, but will take action to maximally exploit their own. Separation of one individual plant into several clones results in a rapid loss of each sibling's original self-identity. When grown together, each sibling now comes to regard the others as competitors and exhibits a typical territorial response (Gruntman & Novoplansky, 2004). However, kin recognition is retained in some plants, as competition with strangers is fiercer than with cloned siblings.

Finally, soil mycorrhizae form ubiquitous symbiotic associations with the roots of most higher plants. Their hyphal connections create communication networks as extensive as whole forests in size through which not only water, nitrate

and potassium move from plant to neighbouring plant, but also information is conveyed indicating disease or predator attack, thereby enabling plants to prepare complex defence mechanisms even before an attack (Song *et al*, 2010). Plant behaviour is active, purpose-driven and intentional. In its capability for self-recognition and problem-solving, similarly to the other organisms described in this article, it is thus adaptive, intelligent and cognitive.

In 1902, Charles Minot stated in a speech to the American Association for the Advancement of Science, “A frank unbiased study of consciousness must convince every biologist that it is one of the fundamental phenomena of at least all animal life if not, as is quite possible, of all life. [...] Consciousness is a device to regulate the actions of organisms to accomplish purposes which are useful to organisms and are thus teleological” (Minot, 1902). More than a century later, Minot's insight that consciousness is ubiquitous for all life is finally coming to bear.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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