

# Is it Quantum Sentience or Quantum Consciousness?

## A Review of Social Behaviours Observed in Primitive and Present-Day Microorganisms

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### ABSTRACT

Social and intelligent behavioural designs have been observed in primitive and present day microorganisms in all three kingdoms of life. These behavioural patterns help microorganisms, to understand, evaluate and judge their constantly varying environment. Behaviour is represented as conscious moment, which occurs due to an event, which may be intentional or unintentional. Microorganisms have the capability of displaying behaviours, which can be compared to cognitive actions of the neural system in higher organisms. This review is a collection of social behaviours observed in present-day microorganisms as well as predicted behaviours in microfossils that have been studied so far. The intent of this review is to prove the origin and existence of consciousness or sentient awareness in microorganisms based on which these social behaviours originated and its comparison to multifaceted conscious behaviours observed in higher beings; its correlation to quantum generated consciousness which enables organisms to understand and judge perceptions, which gives the organism a prospect to behave as per will.

**Key Words:** consciousness, sentience, quantum, behaviour, archaea, bacteria, eukarya, microorganisms

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### 1. Introduction

Human based consciousness comprises of, what we see, hear, touch, taste, smell, feel, etc, which is termed as 'phenomenal consciousness' and this has led to a one-way thinking in determining the existence of true consciousness (Clark, 2001). Humans evolved at a much later stage in evolution, before which the earth was dominated by organisms which survived and are still surviving based on their manipulative intelligence, to perceive and understand the environment. Conscious behaviours observed in

microorganisms may not be similar to human consciousness but are unique in their own space. Superiority does not exist and cannot be falsely determined by the brain size or its capacity, as organisms much smaller have demonstrated capabilities which cannot be matched to human intelligence, especially when the human genome has almost 150 genes that have originated from microorganisms and viruses (Crisp *et al.*, 2015).

Several forms of conscious behaviours are known to exist in organisms ranging from viruses to humans and there is no reason why arguments

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for possession of consciousness must be backed by the existence of the nervous system, which is a wonderful system, but in its own place and organism. In a recent study, the social IQ score for a bacterium *Paenibacillus vortex* was found to be the highest among the 500 bacteria, whose genomes were sequenced. This score was determined based on the number of genes that are needed by the bacteria to communicate and process information about the environment, to make decisions for synthesizing offensive and defensive agents as a mode of protection. The IQ score of these bacteria was found to be three standard deviations higher than the average brilliant social skills demonstrated by some of the renowned scientists of the world (Sirota-Madi *et al.*, 2010).

According to Chris King, the computational power of the bacterial and archaean genome gives a presentation rate of new combinations of up to 1030 bits per second, in comparison to complex life forms, which show a much lower rate of 1017 bits per second, the reason being; few in number, lower reproduction rates and longer generations (King, 2011). According to Lynn Margulis "Not just animals are conscious but every organized being is conscious that is, consciousness is an awareness of the outside world" (Margulis and Sagan, 1995). A similar thought has also been put forward by Humberto Maturana, where he states that "Living systems are cognitive systems and living as a process is a process of cognition. This statement is valid for all organisms with or without a nervous system" (Maturana, 1980; 1970).

Failure to behave like humans does not mean the absence of capability. Simple biological systems such as viruses are capable of making complex joint decisions together with their host e.g. the genetically regulated lambda switch system in a bacteriophage which infects *Escherichia coli*, is a mutual decision taken by both organisms based on the condition of the host cells and number of phages present (Arkin *et al.*, 1998). Many years ago, humans realized that in order to survive they needed to form communities with people of different talents which could be achieved through proper communication and cooperation. Microorganisms are known to display such social behaviours, and through communication and cooperation perform activities such as foraging, biofilm construction, reproduction, signalling, chemical warfare, quorum sensing, etc. They are also known to engage in Hamiltonian descriptions of cooperative

interactions such as altruism, where interactions are beneficial to the recipient but costly to the actor e.g. programmed cell death (PCD) and mutualism, that provides a direct fitness benefit to the organism that performs the behaviour, which outweighs the cost of performing the behaviour e.g. Siderophores (Neilands, 1995).

Many researchers are in the process of understanding the evolution of cooperative behaviours in microorganisms (Crespi, 2001; Velicer, 2003; Travisano and Velicer, 2004; Griffin *et al.*, 2004) and have evidences of conscious social behaviours observed in all their domains of life including bacteria, archaea, viruses, and many unicellular eukaryotes (e.g., some fungi and protists). The microorganisms can therefore, no longer be regarded as simple organisms as they can anticipate, modify and predict changes in the environment with a sense of space and time. At the first annual Francis Crick memorial conference on consciousness held on 7<sup>th</sup> July, 2012, a group of scientists formally declared a document entitled "Cambridge Declaration on Consciousness in Non-Human Animals" which stated that the capacity of consciousness emerged very early in evolution and those processes that support consciousness in humans are likely characteristics of many living organisms (Low, 2012). Evolution is therefore a communication between microorganisms and their environment, a communication that helped trigger multicellularity and the transfer of genetic material from one generation to another by means of reproduction.

Quantum consciousness is computed with of the help of proteins within the cytoskeleton of the cells basic units of life which comprise of unicellular and multicellular animal life (Pereira, 2015b). Evolutionary comparison of the cytoskeleton and its structures suggests that consciousness existed from the very beginning and has been propagating by means of the cytoskeletal network of the cell (Pereira, 2015a) and therefore forms the basis of consciousness for every living being. This review is a collection of some of the interesting social behaviours that have been observed and studied in all three domains of life – Archaea, Bacteria and Eukarya, with the intent to demonstrate the origin and existence of conscious type of behaviours in microorganisms even-though it may not be equivalent or comparable to neural based consciousness. The signal that a microorganism gets from the environment is limited to random noise of the environment which is different as



compared to a neuron in the brain, which gets this signal from a highly coordinated input from other neurons; but generates awareness. In this sense bacteria can be compared to a neuron which through bacterial signalling creates a coordinated input as complex as the brain.

## 2. Predicted social behaviours in primitive microorganisms

Life in the universe only established when a semblance of stability prevailed. In nature, new species have arisen through heredity variation and selection according to laws of nature with those varying in conformity with the environment. Fossil studies have been of substantial evidence in depicting past life events, which can be acknowledged only with strong correlations with various geological endpoints. Microfossils, stromatolites and sedimentary carbon isotope ratios have indicated that microorganisms inhabited the oceans in primitive times and have been recorded in fossils found all over the world (Corsetti *et al.*, 2003). Fossilized stromatolites reefs found in Shark Bay, Western Australia have provided great insights into primitive microbial life, which can be comparable to some of living stromatolites that have been found in recent times e.g. hot springs of Yellowstone National Park (Jahnert and Collins, 2012; Berelson *et al.*, 2011). Fossilized stromatolites are petrological structures that represent lithified forms of microbial life observed in rocks aged 3.6 billion years old. Based on fossil analysis, it has been confirmed that stromatolites were very common in shallow marine environments in the Precambrian age but became rarer in the metazoan or multicellular age (Lepot *et al.*, 2008).

The first signs of cooperative behaviour in microorganisms are based on evidences and studies conducted in the stromatolites that demonstrate the capability of forming loose cooperative communities as a mode of protection, by formation of biofilms, which are now proposed to be the propagators for multicellular life (Lyon, 2007). Mats and biofilms of chemotrophs dated as early as 4000 million years ago depended on hydrothermal vents for their energy source and with the gradual built-up of dead chemotrophs, there would have been an increased possibility of diverse methane-emitting and sulphate-reducing heterotrophic microorganisms (Nisbet and Sleep, 2001). Biofilm and mat formations are need based-architectural designs that have proven to

be a great advantage to microorganisms and were definitely one of the key factors for survival in diverse environments and the initiators for communication and social behaviour (Nadell *et al.*, 2009)

A community with diverse populations of microorganisms gave rise to strong interactions between primordial unicellular organisms, wherein it has been suggested that this primitive form of communication was purely chemical (Bertelson *et al.*, 2012). Perception through cooperation developed the sensing capabilities of these microorganisms and enabled them to gather data from the surroundings giving rise to complex microbial communities, a beginning of primitive social evolution. Fossilized microbial mats dated back to early Archean have shown a pattern of coexistence of bacteria and archaea, consisting of cooperative chemolithotrips in a thermophilic environment. As these interactions in the microbial mats evolved, a diverse population began to exist in these mats with bacteria and archaea fermenters, respirers and methanogens taking up the basal layer of the mats and the cyanobacteria the aerobic layer (Forterre, 2013). This was clearly evident in a stratified stromatolite of the mid-Proterozoic Gaoyuzhuang formation (approximately 1400–1500 million years ago) where a tubular oscillatorian cyanophyte *Siphonophycus inornatum*, showed diurnal growth patterns based on the orientation of the algae in the silica filled layers (Zhang 1986).

Microbial mats studied in hypersaline ponds near Guerrero Negro (Mexico) have shown variation in bacterial populations that live mutually on the same mat and follow behavioural patterns to adjust to their requirements. These microbial mats consist of a layer of photosynthesizing purple bacteria which live along with chemotrophic sulphide-oxidizing and green-sulphur bacteria and have demonstrated migratory behaviour along the mat according to day-night cycles (Harris *et al.*, 2013). Social behaviour evolved with conscious decisions within the microorganism community under the pressure of coordination and cooperation, as a mode to adapt to the ever changing environment. With diversity, different species cooperated and contributed to gain more or less equally or got involved in division of labour, where they would engage in tasks from which they received rewards directly or by benefits to the community. By comparing the characteristics of present day microorganisms with fossils, it may be possible to



predict conscious behavioural patterns which helped propagate evolution of multicellular organisms. Predicted behaviours studied in fossilized microbial mats and stromatolites, suggests that even in a reducing environment, microorganisms were consciously interacting, coordinating and cooperating to adjust and evolve.

### 3. Social behaviours in Archae

Archaea is one of the sub divisions of the phylogenetic classification system that was previously considered as a part of the bacterial group due to its prokaryotic morphology (Smeti *et al.*, 2013). Archaea are a highly conserved primitive group of bacteria which were earlier found only in extremophilic environments (DeLong, 2003) but now have also been found in the human colon and navel (Eckburg *et al.*, 2003). They are therefore considered to be a large diverse group of organisms that are widely distributed in nature. Archaea have shown high levels of lateral gene transfer between lineages and are confirmed to be a separate group of organisms, which evolved in a thermophilic environment with its ancestor being a thermophile (Ochman *et al.*, 2000). The archaeal lineage is one of the known primitive lineages that exists on Earth and is therefore an important link which would help understand Earth's primitive atmosphere and life (Brown and Doolittle, 1997).

Archae are known to survive in extreme environments with high temperatures and are abundant in black smokers, oil wells, geysers, hot springs, etc. They are divided into groups such as halophiles, thermophiles, alkaliphiles and acidophiles based on their presence (Pikuta *et al.*, 2007). Archae are known to mutually exist with other microorganisms which have been observed in several fossilized as well as living microbial mats (Forterre, 2013). Early microbial mats may have been limited to the zones of hydrothermal vents with a colony of single species which diversified to include other species e.g. *Aquifex pyrophillus* is a strict chemolithoautotroph which may have lived alongside hyperthermophilic archaea bacteria like the modern thermoproteus (Strauss *et al.*, 1992). A sense of awareness prevailed within this group of organisms which learned to socially adjust within their microbial mats to accommodate other evolving species. Photosynthesis is also known to have originated as an adaptation of thermotaxis in deep

hydrothermal vents which allowed colonies of mesothermophile bacteria to adapt to photic zones (Nisbet *et al.*, 1995). In present times, mesophilic archaea and several bacteria share the same niche in the oceans and neither of them has shown any signs of extinction (Prosser and Nicol 2008) which demonstrates the capability of microorganisms to be conscious in order to cooperate and survive.

Archaeal halophiles show various adaptive features by which they demonstrate social and cooperative behaviours to survive in extreme conditions. The cell structures of many halophiles show thin, flat pseudo-geometric shapes, which is known to help in nutrient access, cell division and segregation, attachment, motility and survival (Young, 2006). *Haloquadratum walsbyi* or 'salt square' belongs to the genus of the family Halobacteriaceae which show box shaped structures, that give them a higher advantage with survival due to increased surface area (Dyall-Smith *et al.*, 2011). Three similar strains have also been isolated from the brine cultures collected in Sinai, Baja California (Mexico) and southern California (United States) showing similar unique adaptive features (Javor *et al.*, 1982). An additional adaptive feature in these cells, are polyhydroxyalkanoate (PHA) granules and large refractile gas-filled vacuoles which provide buoyancy to the cells to support light harvesting by means of sheet or biofilm formation (Han *et al.*, 2010). Several species of halobacteriales are also known to produce an exopolysaccharide that forms an ion absorbing mucous biofilm, which is another kind of adaptive form, used to regulate transport of ions to survive in hypersaline environments (Christensen 1989; Nicolaus *et al.*, 2003). Thermophilic and mesothermophilic bacteria survive in extreme high temperatures due to the presence of thermophilic enzymes. An increase in extremozyme stability at high temperatures in these organisms which is associated with increased guanine-cytosine base pairs (Kaine, 1990; Saunders *et al.*, 2003).

Adaptive behaviour is a form of social behaviour that is used to adjust to a situation or another form of behaviour (Staddon, 1983). In such high thermophilic and mesophilic environment, archaea have adjusted and adapted to the surroundings in order to survive, as well as mutually adapted to newer species that were in the process of evolving with the rise in oxygen levels in the atmosphere in primitive times. Adaptive form of behaviour is clearly evident in



the primitive microbial mats which portray a combination of survival instinct and social behaviour that existed in the anaerobic environment (Fenchel and Finaly, 2008). Archaea have developed unique adaptive features which has helped these organisms survive and demonstrate social behaviours in extreme conditions. Bacteriorhodopsin is a retinal-protein complex found in *Halobacterium salinarum*, which is used as a transmembrane light-driven proton pump used for energy production (Bhattacharya *et al.*, 2002; Wang *et al.*, 2006a). This form of adaptation is specifically found in halophilic archaea which comprises of an opsin protein and purple retinal that creates a proton gradient which is used by an F-class ATPase to synthesize ATP in anaerobic environments by absorbing photons (Oren, 1999). Methanogens also show such forms of energy-based adaptations. These organisms grow by the conversion of small compounds to methane by generation of ion gradients across the membrane that is used to drive the synthesis of ATP (Godin *et al.*, 2010). Methanogens are also known to share an endosymbiotic relationship with protozoans and by means of their specialized organelles called hydrogenosomes, they generate hydrogen which is taken up by the protozoan (Fenchel and Finlay, 2010). Archaeobacterial evolution is highly based on adaptive social behaviour and can be simply understood as anaerobic thermophilic sulphur-metabolizing form which gave rise to methanogenic and halophilic methanogens and ultimately to aerobic extreme halophiles.

Archaeal microorganisms are flagellated organisms, unlike the cyanobacteria and these structures are a well-built feature used by these organisms to adapt and survive. The motility of archaeal organisms is managed by the rotation of the flagellar bundles which is driven by a biochemical motor and is a feature used during a behavioural response (Bardy *et al.*, 2003). In behavioural studies halobacteria are known to react to light and chemical response and have also shown a learning ability by escaping unfavourable conditions with repetitive insults (Sundberg *et al.*, 1985). Two archaeal organisms, *Methanocaldococcus jannaschii* and *Methanocaldococcus villosus*, were tested to be the fastest archaeal organisms measured as speed as bodies per second (bps) based on their swimming potentials. These flagellated archaeal organism's demonstrated speeds at close to 400 and 500 bps which are high speeds when compared to a

bacteria like *Escherichia Coli* or a fast animal such as a cheetah which move at speeds of 20 bps (Herzog and Wirth, 2012). Finding of new archaeal species and their unique adaptations continues to excite the scientific community and behavioural adaptations of archaea in hypersaline, hyperthermic and hypothermic environments have opened up many areas of research pertaining to the origination of life and the survival instinct of these unique organisms.

Awareness or being conscious holds the key to survival and is displayed by social behaviours in organisms. Adaptive cooperative behaviours observed in archaea, has helped these organisms survive extreme conditions in the past as well as present, which also justifies the fact, that these organisms have the ability of being aware of their surroundings. These were the first organisms to demonstrate cooperative behaviours in microbial mats which originated during the environmental transition period from anaerobic to aerobic form; a beginning of species diversity. Based on behaviours such as mutualism and unique foraging techniques shown by present archaea, we can predict that such behaviours may have been used to survive the ever changing primitive environment.

#### 4. Social behaviours in Bacteria

Chemotaxis, signal transduction and quorum sensing are some of the social and cooperative behaviours observed and studied in bacteria which also resemble some of the most basic functions of the brain, such as sensory integration, memory and decision making (Trewavas and Baluska, 2011). Social and cooperative are a result of cooperative perception that gives bacterial colonies, the ability to sense and gathering data from its surroundings. It also gives them the ability to sense cell densities in order to control factors such as swarming motility, biofilm maturation and antibiotic resistance (Ng and Bassler, 2009). Biofilm formation and quorum sensing have been justified as sensing capabilities and social recognition in bacteria which are also observed in social insects e.g. ants, honey bees, etc (Gibbs *et al.*, 2008). A bacterial biofilm is so well structured that its can sense and communicate messages by means of various techniques of information processing and collective gene regulation which can be suggestive of a lower form of cognitive function and social intelligence (Lyon, 2015). In a recent study, the genus *Burkholderia*

was shown to use quorum sensing for the activation of cellular enzymes for the production of oxalic acid, which neutralized the ammonia related alkaline toxicity during the solitary phase of the bacteria preventing harsh environmental conditions (Goo *et al.*, 2012). This bacterium therefore demonstrated the capability of anticipating a stressful situation and generating a preventive strategy for survival through a conscious decision which may have been voluntary or involuntary.

*Pseudomonas aeruginosa* uses quorum sensing to infect its host system by formation of a biofilm within the host's immune system. During its latency period it can grow within the host without harming it and manipulates its behaviour by sensing its surrounding and coordinating the formation of biofilms, motility and cell aggregation to proceed with the infection (Smith and Iglewski, 2003). Human pathogenic bacteria such as *Salmonella* and *Staphylococcus*, quorum sensing is demonstrated by the release of virulence factors, which helps them cope with the immune system (Deep *et al.*, 2011). Chemotactic behaviour plays a key role in quorum sensing, wherein the bacteria senses and responds to the environment and in pathogenic bacteria is demonstrated by the perception of the stimulus in order to resist the innate and adaptive immune response of their host and survive the antibiotic exposure (Wadhams and Armitage, 2004). Complex gut bacteria in mammals show benefit from social behaviours by means of symbiotic relationship in order to deal with environmental stressors (Dinan *et al.*, 2015). The gut bacteria benefit wholly due to constant source of nutrition to microorganisms which perform functions such as food processing, synthesis of vitamins and inhibition of pathogens (Cecchini *et al.*, 2013; Ramakrishna, 2013).

Bacterial biofilms are structures created due to colonization, wherein the bacterium carries out its duties in a cooperative manner by means of quorum sensing. Biofilms are also created for shelter and procurement of food by means of cooperative behaviour such as foraging (Nadell *et al.*, 2008). *Myxococcus xanthus* is a well-studied soil bacterium, that demonstrates social behaviours as part of its life cycle which includes vegetative growth, predation and development. These bacteria move in a coordinated manner to form organized groups as part of swarming and arrange themselves in stacks. When the swarm encounters a prey, they kill and lyse the cells using

lytic enzymes by a technique called as 'rippling' which helps the bacteria to effectively lyse and absorb the nutrients of the prey (Velicer *et al.*, 2000; Berleman *et al.*, 2008). A similar type of social behaviour is also seen in enteric bacterium *Proteus mirabilis*, which uses the swarming technique for movement of the colony and for collective preying (Wang *et al.*, 2006b). There are several other behaviours in bacteria that have evolved over time as a means to survive and sense the environment in a solitary as well as collective manner. In a group, bacteria are known to survive and multiply through collective sensing, inter-bacterial communication, distributed information processing, joint decision making and dissociative behaviour which have been closely observed in several studies (Popat *et al.*, 2015, Visick and Fuqua, 2005, Bourret and Stock, 2002).

Multifaceted features such as the flagella help the bacteria to pick up and process information about their environment to decide on several actions that need to be taken to survive (Shapiro, 2007). *Escherichia coli* is the most studied flagellated bacterial strain which is known to show complex cooperative behaviour in food foraging and chemotaxis. Environmental condition plays an important role in motility for this bacterium where the flagellum is formed only during unfavourable conditions as a means of protection and survival (Zhao *et al.*, 2007). Under oxidative stress, *E. coli* is known to form colony structures such as spots, stripes and rings which is triggered due to colonial cooperative behaviour to overcome the stress (Budrene and Berg, 1991). *Caulobacter crescentus* is a flagellated bacterium which uses its flagella for swarming behaviour under stress, attaches to a substrate and loses its flagella to become a functional productive stalk, which produces more swimmers as a means of survival (England and Gober, 2001). Some unique behaviours are also seen in cyanobacteria which are known to exhibit a division of labour in relation to food procurement and nitrogen fixation, wherein some bacterial cells convert themselves to heterocysts which are capable of nitrogen fixation but lose their ability to reproduce (Fiore *et al.*, 2010). Heterocysts like structures have been found in fossil records which are 2 billion years old which suggests that this behaviour of differentiation and division of labour existed in earlier prokaryotes (Zhang *et al.*, 2006).

Bacterial parasites are known to demonstrate cooperative behaviour of cheating, during the foraging and swarming phases along



with several myxobacterial species which usually prey using their chemotactic methods and in the process, social parasites cheat, by consuming the partially digested food without utilizing their energy resources e.g. cheating behaviour of *Myxococcus* and *Dictyostelium* (Dao *et al.*, 2000). Chemotaxis and migration are social behavioural responses which bacteria use to find nutrients, avoid toxic chemicals, sense pH and support symbiotic relationships (Shapiro, 2007). Migratory behaviour is also a well-known social behaviour which bacteria use to cope with adverse and varying environmental conditions and also use it to develop an intricate mode of communication. This kind of behaviour has also been observed in mixed bacterial biofilms which show a complex form of interaction and behaviour (Stoodley *et al.*, 1999). Bacteria constantly record information from inside and outside the cell and are aware of their being, and are in a position to raise a conscious thought and record it. In behavioural studies observed in higher beings, movements or reactions performed by an individual due to its sensitivity in response to the environmental changes constitute the behaviour of the individual and the response the individual makes for the environmental changes follows a constant pattern for that individual, thus each individual has its own characteristic behaviour.

Bacterial intelligence is a form of minimal intelligence, which works without a neural system but provides a bacterium the ability to store, modify and execute adaptive processes by means of cooperative multicellular-type behaviours. Conscious decisions help the bacteria to communicate and self-organize into colonies and films which form the basis of multicellular life. The evolution of multicellularity in bacteria may be a possibility, as it has been observed independently in bacteria such as actinomycetes, cyanobacteria and myxobacteria (Bonner, 2001) and can be correlated to a behavioural based activity that needs further evaluation.

## 5. Social behaviours in unicellular Eukarya

Many unicellular eukaryotic organisms are known to demonstrate social and intelligent behaviours and these forms of conscious behaviour as we know, is meant to survive and divide. But there definitely exists some more reason for these organisms to depict such behavioural responses, which are slowly being evaluated in the field of microbial ecology. Some of these behaviours are

known to supersede complex cognitive functions performed by the brain and could be a collective effort demonstrated by the organisms using the most primitive form of consciousness that exist within an individual (Baluška and Mancuso, 2009). Slime moulds or protists are the best examples that demonstrate behaviour similar to neurologically sophisticated organisms e.g. *Physarum polycephalum* (Latty and Beekman, 2010). *Physarum polycephalum* is a protist or slime mould which uses a spatial memory system to navigate through a food maze and is known to find the shortest path using its foraging techniques (Nakagaki *et al.*, 2001). This organism can also memorize the location and avoid the areas of high risk and relocate to areas which are unexplored (Dussutour *et al.*, 2010; Reid *et al.*, 2013). Slime mould *Dictyostelium discoidei* or *Dictyostelium dicodium* is known to form a multicellular slug under conditions of nutritional abundance and upon starvation; cyclic AMP triggers the differentiation of cells and initiates the formation of stalk cells (Bonner, 2008). Risk related avoidance is purely a cognitive behavioural function and is always associated with the neural system but these slime moulds clearly demonstrate the capability of performing such high level conscious behaviours, utilizing their spatial memory capability in the absence of a brain (Adamatzky *et al.*, 2013).

*Amoeba proteus* is a well-known protozoan, known to show several social behavioural responses e.g. regulation in the rate of reproduction based on availability of food, encapsulation, etc (Anderson, 1988). Pseudopodium is a highly defined energy mediated structure formed in amoeba and supports behavioural responses associated with procurement of food as well as exhibiting a choice for food. They also demonstrate the capability of differentiating between inorganic and organic food and can isolate an unknown object from an engulfed food particle (Parsons, 1926; Mast and Hahnert, 1935). Division of labour among the organelles in amoeba is evident when compared to higher organisms, where the food cup resembles the buccal cavity; the food vacuole resembles the gut, the pseudopodia the legs and the contractile vacuole the urinary bladder (Bonner, 2009; Jeon, 1995). Amoeba has no structures for reception of stimuli but the protoplasm is aware and responds to a stimulus, which gives it the ability to perceive and recognize its own kind and engage in cooperative behaviour.

Cognitive smartness and intelligence in these organisms, supports social behaviours related to learning, memory, anticipation and risk management (Gregor *et al.*, 2010).

Euglena exhibits behavioural responses to various stimuli that are highly sensitive to the stimulus of light. These organisms are known to group themselves in a location where there is a balance of light and darkness and uses its flagellum in rotator manner to organize itself. In unfavourable conditions it undergoes encystment by losing its flagella and secretes a cyst (Diehn, 1973). The protozoan parasite *Trypanosoma cruzi*, demonstrates similar behavioural patterns in the blood of vertebrates (Noireau *et al.*, 2009). *Vorticella convallaria* is a stalked ciliated protozoan that exhibits a sensitive behavioural response to mechanical stimulus and is known to coil instantaneously into a tight spiral with the slightest impact which is caused due to a membrane depolarization (Shiono and Naitoh, 1997). Volvox is a colonial flagellate and shows a transition between unicellular to multicellular form. The flagellar movement of each of the cells in the colony help in the movement of the whole colony which is a mutual colonized social behaviour demonstrated by these organisms as a means of protection and movement towards light (Solari, 2011). During unfavorable or shortage of food, ciliated protists such as *Loxophyllum meleagris* demonstrates a social behavioural response. These organisms cease to feed and then seek out another of the same species; mutually inspect them and then join to form a pair by fusing and exchange nuclei in a microbial embrace (Holmes, 2005).

*Elphidium excavatum clavatum* or *Polystomella crispa* are known to use behavioural instincts to build their protective structures by seeking out the correct frustules, identifying them and cementing them together as a shell (Schonfeld and Numberger, 2007; Murray, 2012). Tintinnid ciliates show a similar behaviour and gather fragments of rock and tiny particles of quartz and cement it together to make the lorica or protective chamber in the shape of a bell (Durmus and Balkis, 2014). Locating, sensing, identifying and selecting mineral fragments into a delicate shell are complex behaviours beyond the understanding of biologists (Ford, 2004). Clark studied the mating behaviour of *Spirostomum ambiguum*, which is a ciliated organism that is known to advertise mating fitness to suitors during courtship. In his study, he defined fit suitors as, conspicuous

consumers and less fit suitors as prudent savers and demonstrated that both these types of suitors learn to switch between forms to optimize mate selection through behavioural responses (Clark, 2012). Paramecium is another organism that has been widely studied for its behaviour. Movement is performed by metaboly, body contortions or by cilia and if the organism is touched by a pointed object, it becomes conscious, the ciliary beat reverses and the animal moves backward by rotating in a conical path (Jensen, 1959; Harvey and Bovell, 2006). Generation of a conscious moment in paramecia is depicted as a behavioural response or a sense of awareness to a stimulus which helps the organism understand its surroundings (Jennings, 1905/1962; Hameroff, 2012).

Understanding and reasoning forms the basis for intelligence in many unicellular organisms which survive, based on the ability to perform cognitive functions without the presence of a neural system (Shapiro, 2007). This kind of intelligence cannot be compared to the intelligence observed in higher organisms, but does show some overlap in areas of mental activity, memory and learning (Westerhoff *et al.*, 2014). Eukaryotic microorganisms demonstrate the presence of intelligence in its lowest form, which has evolved to a higher state as a form of adaptation by means of cell division and cell differentiation in higher organisms depicted by similarity in social behaviours (Marijuan *et al.*, 2013). Further evaluation of studies in the area of behavioural sciences in eukaryotic microorganisms would help evaluate the possibility of a correlation of cognitive behaviours observed in higher and lower organisms from an evolutionary standpoint.

## 6. Conclusions

In a cell or a group of cells e.g. a microbial mat or a developing embryo, the cells always demonstrate an involuntary behaviour programmed through genetic makeup which appears as a habit and may not be due to consciousness per se but the reason to behave is act of learning which may originate through consciousness; for a cell needs to be aware for it to learn and behave and therefore even though behaviour and consciousness are two separate entities, they complement each other. Therefore, in case of a formation of a microbial mat or a developing embryo, the cell or cells are aware; aware of its surroundings; aware of the





need for cell division; aware of organizing themselves into mats; therefore, behaving as per will. Sentience or conscious behaviour is prevalent in all three domains of the unicellular kingdom and in comparison to the neural system, is in lower form, but by division of labour in cells it propagates and attains a higher state, as observed in higher organisms.

Whether unicellular or multicellular, we all depend on our past experiences and observation and use this for several actions that need to be performed in our day to day life, which is managed by the conscious decisions that we take, which may be new or retrieved from memory. The protoplasm in the cell of all organisms is unique and for microorganisms it holds the ability to store and retrieve memory, acting as a store house of intelligence. It has the ability to make an organism conscious of its surroundings and its main effort is to gain a clear perception to associate and recognize favourable and unfavourable conditions, just like the brain in higher organisms. Acquisition of knowledge is based on sense-perception, which in microorganisms is acquired as a conscious moment and with time, becomes a reflex moment that gets repeated as per requirement e.g. foraging for food (Radnitzky *et al.*, 1993).

Quantum based consciousness computed in microtubules via the ORCH-OR theory of Hameroff and Penrose (Hameroff and Penrose, 2014) originates within every cell of all unicellular and multicellular organisms and therefore forms the support mechanism for important functions managed at a cellular level such as cell proliferation and differentiation, apoptosis, DNA synthesis, RNA transcription, protein expression, ATP synthesis and metabolic activity. Quantum consciousness enables animals to understand and judge perceptions, which gives the animal a prospect to behave as per will. Social behaviours in microorganisms whether present or fossilized, have helped answer several questions in relation to conscious and intelligent decisions in absence of neural systems. Whether this type of consciousness is primitive, proto or simple needs to be evaluated but it is definitely some type of consciousness that microorganisms use, to survive. Future research in this area is needed which could provide a better understanding about, how consciousness is generated and propagated in microorganisms of all domains of life. Consciousness or conscious behaviour is an awareness of the external world and cannot be restricted to neurons or the neural system.

## References

- Adamatzky A, Armstrong R, Jones J, Gunji Y. On creativity of slime mould. *Int J Gen Sys* 2013; 42: (5) 441-457, doi:10.1080/03081079.2013.776206.
- Anderson OR. *Comparative Protozoology: Ecology, Physiology, Life History*. Springer-Verlag; 1 ed. 1998.
- Arkin A, Ross J, McAdams HH. Stochastic Kinetic Analysis of Developmental Pathway Bifurcation in Phage  $\lambda$ -Infected *Escherichia coli* Cells. *Genetics* 1998; 149(4): 1633-1648.
- Baluška F, & Mancuso S. Deep evolutionary origins of neurobiology. Turning the essence of 'neural' upside-down. *Commun. Integr. Biol.* 2009; 2(1): 60-65.
- Bardy SL, Ng SYM, Jarrell KF. Prokaryotic motility structures. *Microbiol* 2003; 149 (2): 295-304. doi: 10.1099/mic.0.25948-0.
- Bhattacharya P, Xu J, Varo G, Marcy DL, Birge RR. Monolithically integrated bacteriorhodopsin-GaAs field-effect transistor photoreceiver. *Opt Lett* 2002; 27(10): 839-41.
- Berelson WM, Corsetti FA, Pepe-Ranney C, Hammond DE, Beaumont W, Spear JR. Hot spring siliceous stromatolites from Yellowstone National Park: assessing growth rate and laminae formation. *Geobiol* 2011; 9: 411-424.
- Berleman JE, Scott J, Chumley T, Kirby JR. (2008). Predatation behavior in *Myxococcus Xanthus*. *PNAS* 2008; 105 (44): 17127-17132. doi:10.1073.pnas.0804387105.
- Bertelson P, Hutton R, McClure K. (Workshop Overview). *The Social Biology of Microbial Communities: Workshop Summary*. Institute of Medicine (US) Forum on Microbial Threats. Washington (DC): National Academies Press (US). 2012.
- Brown JR & Doolittle WF. Archaea and the Prokaryote-to-Eukaryote Transition. *Microbiol Mol Biol Rev* 1997; 61: 456 - 502.
- Bonner JL. *The Social Amoebae: The Biology of Cellular Slime Molds*. Princeton University Press, 2008.
- Bonner JT. *First Signals: The Evolution of Multicellular Development*. Princeton University Press, 2001.
- Bourret RB & Stock AM. Molecular Information Processing: Lessons from Bacterial Chemotaxis. *J Biol Chem* 2002; 277: 9625-9628. doi: 10.1074/jbc.R100066200.
- Budrene E & Berg H. Complex patterns formed by motile cells of *Escherichia coli*. *Nature* 1991; 349: 630-633.
- Cecchini DA, Laville E, Laguerre S, Robe P, Leclerc M, Dore J. *et al*, Functional metagenomics reveals novel pathways of prebiotic breakdown by human gut bacteria. *PloS One* 2013; 8 (9). doi: 10.1371/journal.pone.0072766.
- Christensen BE. The role of extracellular polysaccharides in biofilms. *J Biotech* 1989; 10: 181-202.
- Clark A. Phenomenal consciousness so-called. In Werner Backhaus, (ed), *Neuronal Coding of Perceptual Systems*. New Jersey: World Scientific, Series on Biophysics and Biocybernetics 2001; 9: 405 -422.
- Clark KB. Social biases determine spatiotemporal sparseness of ciliate mating heuristics. *Commun Integr Biol* 2012; 5(1): 3-11.
- Corsetti FA, Awramik SM, Pierce D. A complex microbiota from snowball Earth times: microfossils from the Neoproterozoic Kingston Peak Formation, Death Valley, USA. *Proc Natl Acad Sci* 2003; 100(8): 4399-4404.
- Crespi BJ. The evolution of social behavior in microorganisms. *Trends Ecol Evol* 2001; 16: 178-183.
- Crisp A, Boschetti C, Perry M, Tunnacliffe A, Micklem G. Expression of multiple horizontally acquired genes is a hallmark of both vertebrate and invertebrate genomes. *Genome Biol* 2015; 16: 50. doi: 10.1186/s13059-015-0607-3.
- Dao DN, Kessin RH, Ennis HL. Developmental cheating and the evolutionary biology of *Dictyostelium* and *Myxococcus*. *Microbiol* 2000; 146 (7): 1505-1512.
- Deep A, Chaudhary U, Gupta V. *Quorum sensing and Bacterial Pathogenicity: From Molecules to Disease*. *J Lab Physicians* 2011; 3(1): 4-11. doi: 10.4103/0974-2727.78553.
- DeLong EF. Oceans of Archaea. *ASM News* 2003; 69: 10.
- Diehn B. Phototaxis and sensory transduction in *Euglena*. *Science* 1973; 14: 181(4104), 1009-1015.
- Dinan TG, Stilling RM, Stanton C, Cryan JF. Collective unconscious: How gut microbes shape human behaviour. *J Psych Res* 2015; 63: 1-9.
- Durmus T & Balkis N. Tintinnid (Protozoa: Ciliophora) species in the Gulf of Gemlik and some ecological properties of the environment. *Fresenius Environ Bull* 2014; 23 (12): 2991 - 2997.
- Dussutour A, Latty T, Beekman M, Simpson SJ. Amoeboid organism solves complex nutritional challenges. *PNAS* 2010; 107 (10). doi: 10.1073/pnas.0912198107.
- Dyall-Smith ML, Pfeiffer F, Klee K, Palm P, Gross K, Schuster SC, Rampp M, Oesterheld D. *Haloquadratum walsbyi*: Limited Diversity in a Global Pond. *PLoS One* 2011; 6 (6): 1-23. doi:10.1371/journal.pone.0020968.
- Eckburg PB, Lepp PW, Relman DA. Archaea and Their Potential Role in Human Disease. *Infect Immun* 2003; 71 (2): 591-596. doi: 10.1128/IAI.71.2.591-596.
- England JC, Gober JW. Cell cycle control of cell morphogenesis in *Caulobacter*. *Curr Opin Microbiol* 2001; 4(6):674-80.
- Fenchel T & Finlay B. *Free-Living Protozoa with Endosymbiotic Methanogens*. J.H.P. Hackstein (ed.), (Endo)symbiotic Methanogenic Archaea, *Microbiology Monographs* 2010; 19, doi: 10.1007/978-3-642-13615-3\_1, # Springer-Verlag Berlin Heidelberg.
- Fenchel T & Finlay B. Oxygen and the Spatial Structure of Microbial Communities. *Biol Rev* 2008; 83: 553-569. doi:10.1111/j.1469-185X.2008.00054.x.
- Fiore CL, Jarett JK, Olson ND, Lesser MP. Nitrogen fixation and nitrogen transformations in marine symbioses. *Trends in Microbiology* 2010; 18 (10): 455-463.
- Ford BJ. Are cells ingenious? *Microscope* 2004; 52:3/4, 135 - 144.
- Forterre P. The Common Ancestor of Archaea and Eukarya Was Not an Archaeon. *Archaea* 2013; 18. <http://dx.doi.org/10.1155/2013/372396>.
- Gibbs KA, Urbanowski ML, Greeberg EP. Genetic determinants of self identity and social recognition in bacteria. *Science*. 2008; 321(5886): 256-259 doi: 10.1126/science.1160033.
- Gregor T, Fujimoto K, Masaki N, Sawai S. The Onset of Collective Behavior in Social Amoebae. *Science* 2010; 328 (5981). 1021-1025. DOI: 10.1126/science.1183415.
- Godin A, McLaughlin JW, Webster KL, Packalen M, Basiliko N. Methane and methanogen community dynamics across a boreal peatland nutrient gradient. *Soil Biol Biochem* 2012; 48: 96-105. doi:10.1016/j.soilbio.2012.01.018.
- Goo E, Majerczyk CD, Hyung An A, Chandler JR, Seo Y, Ham H, Lim JY, Kim H., Lee B, Jang MS, Greeberg EP, Hwang I. Bacterial quorum sensing, cooperativity, and anticipation of stationary-phase stress. *Proc Natl Acad Sci USA* 2012; 109(48); 19775-19780. doi: 10.1073/pnas.1218092109.
- Griffin AS, West SA, Buckling A. Cooperation and competition in pathogenic bacteria. *Nature* 2004; 430: 1024-1027.
- Hammeroff S. How quantum brain biology can rescue conscious free will. *Front Integr Neurosci* 2012; 6: 93. doi: 10.3389/fnint.2012.00093.



- Hameroff, S. & Penrose, R. Consciousness in the universe. A review of the 'Orch OR' theory. *Phys Life Rev* 2014; 11: 39–78.
- Han J, Hou J, Liu H, Cai S, Feng B, Zhou J, Xiang H. Wide Distribution among Halophilic Archaea of a Novel Polyhydroxyalkanoate Synthase Subtype with Homology to Bacterial Type III Synthases. *Appl Environ Microbiol*. 2010; 76(23): 7811–7819. doi: 10.1128/AEM.01117-10.
- Harris JK, Caporaso JG, Walker JJ, Spear JR, Gold NJ, Robertson CE, Hugenholtz P, Goodrich J, McDonald D, Knights D, Marshall P, Tufo H, Knight R, Pace NR. Phylogenetic stratigraphy in the Guerrero Negro hypersaline microbial mat. *The ISME Journal* 2012; 7: 50–60. doi:10.1038/ismej.2012.79.
- Harvey AW & Bovell NK. Spontaneous alternation behavior in *Paramecium*. *Learn Behav* 2006; 34(4): 361-5.
- Herzog B & Wirth R. Swimming Behavior of Selected Species of Archaea. *App Environ Microbiol* 2012; 78(6):1670-4. doi: 10.1128/AEM.06723-11.
- Holmes SJ. The behavior of *Loxophyllum* and its relation to regeneration. *J Exp Zoo* 2005; 4(3):399–418. DOI: 10.1002/jez.1400040304.
- Jahnert RJ & Collins LB. Characteristics, distribution and morphogenesis of subtidal microbial systems in Shark Bay, Australia. *Marine Geology* 2012; 303–306, 115–136.
- Javor B, Requadt C, Stoekenius W. Box-shaped halophilic bacteria. *J Bacteriol* 1982; 151(3): 1532–1542.
- Jennings HS. Behavior of the Lower Organisms. 1905/1962. Bloomington: Indiana University Press.
- Jensen DD. A Theory of the Behavior of *Paramecium aurelia* and Behavioral Effects of Feeding, Fission, and Ultraviolet Microbeam Irradiation. *Behaviour* 1959; 15(1/2): 82–122.
- Jeon KW. The large, free-living amoebae: wonderful cells for biological studies. *J Eukaryot Microbiol* 1995; 42: 1–7.
- Kaine BP. Structure of the archaeobacterial 7S RNA molecule. *Molecular and General Genetics* 1990; 221(3): 315–321.
- King C. Cosmological foundations of Consciousness. *J Cosmol* 2011; 14. <http://journalofcosmology.com/Consciousness103.html>. Accessed on 22nd May 2015.
- Latty T & Beekman M. Food quality and the risk of light exposure affect patch-choice decisions in the slime mold *Physarum polycephalum*. *Ecology* 2010; 91(1): 22–27.
- Lepot K, Benzerara K, Brown GE, Philippot P. Microbially influenced formation of 2.7 billion-year-old stromatolites. *Nature Geoscience* 2008; 1 (2): 118–21.
- Low P. Consciousness in human and non-human animals. The Francis Crick Memorial Conference, eds Panksepp J, et al., (Cambridge, UK). 2012. Available at <http://fcmconference.org/img/CambridgeDeclarationOnConsciousness.pdf>. Accessed April 10, 2015.
- Lyon P. The cognitive cell: bacterial behavior reconsidered. *Front Microbiol* 2015; 6: 264. doi: 10.3389/fmicb.2015.00264.
- Lyon P. From quorum to cooperation: lessons from bacterial sociality for evolutionary theory. *Studies in History and Philosophy of Science Part C: Studies in History and Philosophy of Biological and Biomedical Sciences* 2007; 38(4): 820–833.
- Margulis L & Sagan D. What is life? The Eternal Enigma. University of California Press, 1995.
- Marijuán PC, del Moral R, Navarro J. On eukaryotic intelligence: signaling system's guidance in the evolution of multicellular organization. *Biosystems* 2013; 114(1): 8–24. doi: 10.1016/j.biosystems.2013.06.005.
- Mast SO & Hahnert WF. Feeding, Digestion, and Starvation in *Amoeba proteus* (Leidy). *Physiological Zoology* 1935; 8: (3), 255–272.
- Maturana HR. Biology of Cognition. Biological Computer Laboratory Research Report BCL 9.0. Urbana IL: University of Illinois, 1970. As Reprinted in: Autopoiesis and Cognition: The Realization of the Living. Dordrecht: D. Reidel Publishing Co. 1980; 5: 58.
- Murray JW. Unravelling the life cycle of *Polystomella crista*: the roles of Lister, Jepps and Myers J. *Micropalaeontology* 2012; 31:121-129, doi: 10.1144/0262-821X11-034.
- Nadell C, Xavier JB, Kevin R, Foster KR. The socio-biology of biofilms. *FEMS Microbiol Rev* 2009; 1: 19.
- Nadell CD, Bassler BL, Levin SA. Observing bacteria through the lens of social evolution. *J Biol* 2008; 7: 27. doi:10.1186/jbiol87.
- Nakagaki T, Yamada H, Tóth A. Path finding by tube morphogenesis in an amoeboid organism. *Biophys Chem* 2001; 92: 47–52.
- Neilands JB. Siderophores: Structure and Function of Microbial Iron Transport Compounds. *J Biol Chem* 1995; 270 (45): 26723 – 26726. doi:10.1074/jbc.270.45.26723.
- Ng W & Bassler BL. Bacterial quorum-sensing network architectures. *Annu Rev Genet* 2009; 43:197-222. doi: 10.1146/annurev-genet-102108-134304.
- Nicolaus B, Schiano MV, Lama L, Poli A, Gambacorta A. Polysaccharides from extremophilic microorganisms. *Origins of Life and Evolution of Biospheres* 2003; 34: 159–169.
- Nisbet EG & Sleep NH. The habitat and nature of early life. *Nature* 2001; 409: 1083-1091 doi:10.1038/35059210.
- Nisbet EJ, Cann JR, Lee C, Dover V. Origins of photosynthesis. *Nature* 1995; 373: 479 – 480. doi:10.1038/3737479a0.
- Noireau F, Diosque P, Jansen AM. *Trypanosoma cruzi*: adaptation to its vectors and its hosts. *Vet Res* 2009; 40(2): 26. doi: 10.1051/vetres/2009009.
- Ochman H, Lawrence JG, Groisman EA. Lateral gene transfer and the nature of bacterial innovation. *Nature* 2000; 405: 299 – 304.
- Oren A. Bioenergetic aspects of halophilism. *Microbiol. Mol Biol Rev* 1999; 63, 334–348.
- Parson CW. Some observations on the behaviour of *Amoeba proteus*. *Quarterly Journal of Microscopical Sciences* 1926; 2-70: 629-646.
- Pereira C. Cytoskeleton and Consciousness: An Evolutionary Based Review. *NeuroQuantology* 2015 a; 13 (2): 232-239.
- Pereira C. Quantum Consciousness in Animals. *Journal of Metaphysics and Connected Consciousness* 2015 b (August 2015).
- Pikuta EV, Hoover RB, Tang J. Microbial extremophiles at the limits of life. *Crit Rev Microbiol* 2007; 33 (3): 183–209. doi:10.1080/10408410701451948.
- Popat R, Cornforth DM, McNally L, Brown SP. Collective sensing and collective responses in quorum-sensing bacteria. *J R Soc Interface* 2015; 12 (103): DOI: 10.1098/rsif.2014.0882.
- Prosser JI & Nicol GW. Relative contributions of archaea and bacteria to aerobic ammonia oxidation in the environment. *Environ Microbiol* 2008; 210(11): 2931-41. doi: 10.1111/j.1462-2920.2008.01775.x.
- Radnitzky G, Bartley WW, Popper K. *Evolutionary Epistemology, Rationality, and the Sociology of Knowledge*. 1993. Open Court Publishing Company; Third Printing edition (March 1, 1993).
- Ramakrishna BS. Role of the gut microbiota in human nutrition and metabolism. *J Gastroenterol Hepatol* 2013; 28 (4): 9–17.



- Reid CR, Beekman M, Latty T, Dussutour, A. Amoeboid organism uses extracellular secretions to make smart foraging decisions. *Behavioral Ecology* 2013; 24 (4): 812-818. doi: 10.1093/beheco/art032.
- Saunders NF, Thomas T, Curmi PM, Mattick JS, Kuczek E, Slade R, Davis J, Franzmann PD. et al. Mechanisms of thermal adaptation revealed from the genomes of the Antarctic Archaea *Methanogenium frigidum* and *Methanococcoides burtonii*. *Genome Research* 2003; 13: 1580-1588.
- Schonfeld J & Nunberger L. Seasonal dynamics and decadal changes of benthic foraminiferal assemblages in the western Baltic Sea (NW Europe). *J Micropalaeontology* 2007; 26: 47-60. doi: 10.1144/jm.26.1.47.
- Shapiro JA. Bacteria are small but not stupid: cognition, natural genetic engineering and socio-bacteriology. *Studies in History and Philosophy of Biological and Biomedical Sciences* 2007; 38: 807-819.
- Shiono H & Naitoh Y. Cellular contraction precedes membrane depolarization in *Vorticella convallaria*. *J Exp Biol* 1997; 200: 2249-2261.
- Sirota-Madi A, Olender T, Helman Y, Ingham C, Brainis I, Roth D, Hagi, E, Brodsky L, Leshkowitz D, Galatenka V, Nikolaev V, Mugasimangalam RC, Bransbury-Zabary S, Gutnick DL, Lancet D, Ben-Jacob E. Genome sequence of the pattern forming *Paenibacillus vortex* bacterium reveals potential for thriving in complex environments. *BMC Genomics* 2010; 11: 710. doi:10.1186/1471-2164-11-710.
- Smetia E, Kormasb K, Spatharis S. A non-phylogenetic alpha diversity approach on prokaryotic community structure in aquatic systems. *Ecological Indicators* 2013; 29: 361-366.
- Smith RS & Iglewski BH. *Pseudomonas aeruginosa* quorum sensing as a potential antimicrobial target. *J Clin Invest* 2003; 112(10): 1460-1465. doi:10.1172/JCI20364.
- Solari CA. The flagellar photoresponse in *Volvox* species (Volvocaceae Chlorophyceae). *J Phycol* 2011; 47: 580-583.
- Staddon JER. *Adaptive Behavior and Learning*. 1983, Cambridge University Press.
- Stoodley P, Lewandowski Z, Boyle JD, Lappin-Scott HM. The formation of migratory ripples in a mixed species bacterial biofilm growing in turbulent flow. *Environ Microbiol* 1999; 1(5): 447-455.
- Strauss G, Eisenreich W, Bacher A, Fuchs G. <sup>13</sup>C-NMR study of autotrophic CO<sub>2</sub> fixation pathways in the sulfur-reducing Archaeobacterium *Thermoproteus neutrophilus* and in the phototrophic Eubacterium *Chloroflexus aurantiacus*. *European J Biochem* 1992; 204: 853-866.
- Sundberg S, Bogomolni RA, Spudichi JL. Selection and properties of phototaxis-deficient mutants of *Halobacterium halobium*. *J Bact* 1985; 164 (1): 282-287.
- Travisano M & Velicer GJ. Strategies of microbial cheater control. *Trends Microbiol* 2004; 12: 72-78.
- Trewavas AJ & Baluska F. The ubiquity of consciousness. The ubiquity of consciousness, cognition and intelligence in life. *EMBO Rep* 2011; 12(12): 1221-1225. doi: 10.1038/embor.2011.218.
- Velicer GJ. Social strife in the microbial world. *Trends Microbiol*. 2003; 11, 330-337.
- Velicer GJ, Kroos L, Lenski RE. Developmental cheating in the social bacterium *Myxococcus Xanthus*. *Nature* 2000; 404 (6778): 598-601.
- Visick KL & Fuqua C. Decoding Microbial Chatter: Cell-Cell Communication in Bacteria. *J Bacteriol* 2005; 187(16): 5507-5519. doi: 10.1128/JB.187.16.5507-5519.2005.
- Wadhams GH & Armitage JP. Making sense of it all: bacterial chemotaxis. *Nature Reviews Molecular Cell Biology* 2004; 5: 1024-1037. doi:10.1038/nrm1524.
- Wang WW, Knopf GK, Bassi AS. Photoelectric properties of a detector based on dried bacteriorhodopsin film. *Biosensors and Bioelectronics* 2006a; 21 (7): 1309-1319.
- Wang W, Lai H, Hsueh P, Chiou RY, Lin S, Liaw S. Inhibition of swarming and virulence factor expression in *Proteus mirabilis* by resveratrol. *J Med Microbiol* 2006b; 55 (10): 1313-1321. doi: 10.1099/jmm.0.46661-0.
- Westerhoff HV, Brooks AN, Simeonidis E, Garcia-Contreras R, He F, Boogerd FC, Jackson VJ, Goncharuk V, Kolodkin A. Macromolecular networks and intelligence in microorganisms. *Front Microbiol* 2014; 5: 379. doi: 10.3389/fmicb.2014.00379.
- Young KD. The Selective Value of Bacterial Shape. *Microbiol Mol Biol Rev* 2006; 70(3): 660-703. doi: 10.1128/MMBR.00001-06.
- Zhang JY, Chen WL, Zhang CC. *hetR* and *patS*, two genes necessary for heterocyst pattern formation, are widespread in filamentous nonheterocyst-forming cyanobacteria. *Microbiol* 2009; 155 (5): 1418-1426.
- Zhang Z. Solar cyclicity in the Precambrian microfossil record. *Paleontology* 1986; 29 (1): 101 - 111.
- Zhao K, Liu M, Burgess RR. Adaptation in bacterial flagellar and motility systems: from regulon members to 'foraging'-like behavior in *E. Coli*. *Nucleic Acids Res* 2007; 35(13): 4441-4452. doi: 10.1093/nar/gkm456.