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J. Shashi Kiran Reddy
National Institute of Advanced Studies

Contzen Pereira

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Understanding the emergence of microbial consciousness: From a perspective of the Subject–Object Model (SOM)

J. Shashi Kiran Reddy [a,*] and Contzen Pereira [b]
[a] *Independent Research Scholar, Bangalore 560064, India*
E-mails: jumpalreddy@live.com, jumpal_shashi@yahoo.com
[b] *Independent Researcher, Mumbai 400 099, India*
E-mails: contzen@rediffmail.com, contzen@gmail.com

Abstract. Microorganisms demonstrate conscious-like intelligent behaviour, and this form of consciousness may have emerged from a quantum mediated mechanism as observed in cytoskeletal structures like the microtubules present in nerve cells which apparently have the architecture to quantum compute. This paper hypothesises the emergence of proto-consciousness in primitive cytoskeletal systems found in the microbial kingdoms of archaea, bacteria and eukarya. To explain this, we make use of the Subject–Object Model (SOM) of consciousness which evaluates the rise of the degree of consciousness to conscious behaviour in these systems supporting the hypothesis of emergence and propagation of conscious behaviour during the pre-Cambrian part of Earth's evolutionary history. Consciousness as proto-consciousness or sentience computed via primitive cytoskeletal structures substantiates as a driver for the intelligence observed in the microbial world during this period ranging from single-cellular to collective intelligence as a means to adapt and survive. The growth in complexity of intelligence, cytoskeletal system and adaptive behaviours are key to evolution, and thus supports the progression of the Lamarckian theory of evolution driven by quantum mediated proto-consciousness to consciousness as described in the SOM of consciousness.

Keywords: Proto-Consciousness, cytoskeleton, Orch-OR theory, microbial intelligence, Lamarckian theory, quantum biology, SOM

1. Introduction

The most fundamental physical mechanisms which are involved in the biological systems are dealt and studied in the new branch of science called Quantum biology. Findings resulting from these investigations shed light on the possible role of quantum mediated processes in crafting the primitive life forms and in the emergence of conscious life. Since biological evolution began much after the existence of energy and matter and its unanimity, the answer to the origin of life actually lies much before the emergence of viruses, bacteria, archaea and eukaryotes. According to Gaia theory, after the formation of biological matter from chemical constituents there exists a mutual and dynamic interaction between the two resulting in the process of co-evolution. This means that biological systems interact with surrounding inorganic matter to form a complex, self-regulating and dynamic synergistic system of ecology which helps in perpetuating and maintaining the conditions for life (Schneider and Boston [68]).

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[*] Corresponding author. E-mails: jumpalreddy@live.com, jumpal_shashi@yahoo.com.

The formation of the first biological cell forms the basis for all life that now exists on the Gaia. Such an event is supported by various theories and hypotheses, but with their own pros and cons (Sheldrake [69], William [84], Lipton [39], Lanza and Berman [37], Reddy and Pereira [62,64]). With the increased degrees of freedom driven by various ecological factors this cellar unit slowly started acting as a separate entity by itself. The survival necessity of this entity could have triggered the development of various adaptive mechanisms and every step towards adapting to the environment slowly, might have resulted in a qualitative property called intelligence, and every action motivated from this intelligence field resulting in a specific behaviour. Environmental and other interactive forces keep these units in a constant survival challenge and hence create the need for mutual support for the sake of one's existence. As stated above, quantum biology is now starting to solve the mysteries associated with the field of evolutionary biology and the origin of life. Though the evolution of life or consciousness in general is a wide theme to be addressed, in the scope of the present paper, we focus our attention to the study of emergence of consciousness in the microbial systems. For this purpose, we make use of the Subject–Object Model (SOM) of consciousness developed by one of the present authors (Reddy [59]) and extrapolate the Orchestrated Objective Reduction (Orch-OR) theory put forth by Hameroff and Penrose [26]. Since the SOM of consciousness supports the presence of consciousness in all living systems to varying levels and degrees; which again depends on where a specific species would fall on the evolutionary scale, it naturally supports the pansychic view of the world.

In order to understand the evolutionary footsteps of consciousness, one needs a different definition and perspective of consciousness from that which we observe in humans. Humans can relate and express their conscious experiences of life and hence we can set a standard to quantify them, but this is not the case with other living systems. They exhibit different forms of conscious expressions as observable behaviour and survival strategies etc. Hence, when we study the evolution of conscious life in these systems, we need to consider the alterate expressions of consciousness like conscious behaviour as the deciding and judging criteria. Several forms of conscious behaviours are known to exist across the wide spectra of non-humans species, and hence there is no reason why arguments for possession of consciousness must be backed by the existence of the nervous system; a unique and complex functional system, but in its own place and organism. Though conscious behaviours observed in microorganisms may not be similar to that of humans, they are unique in their own space; therefore many scientists preferably use the terminology as *sentience* or *proto-consciousness*. In the context of this paper, we discuss the conscious behaviours exhibited by various microbial systems to understand the primitive forms of conscious expressions along with the evolving cytoskeleton.

Based on fossil evidence, microbes occupied approximately 2.75–3 billion years of Earth's evolutionary history; the pre-Cambrian period with free-living, single-celled organisms (Tomescu et al. [75]). Some microorganisms initially embraced living in isolation but gradually formed loose communities or colonies as part of the evolutionary advantage to evolve as a reflection of the biological imperative to survive. About 1.5 billion years ago, eukaryotic cells appeared apparently as symbiotic mergers of previously independent organelles such as mitochondria, plastids, etc. with the prokaryotic cells (Knoll et al. [35]). At later stages, sentient or proto-consciousness driven differentiation, organization and socialization were some of the evolutionary advantages which expedited the evolutionary process in the microbial world (Fabbro et al. [17]). Here, consciousness as proto-consciousness was the biggest driver for intelligence observed in the microbial world which resulted in emergence of single-cellular and collective intelligence. Therefore the emergence of primitive forms of consciousness was evident with the rise in intelligent behaviour within the world of microbes that occupied a major portion of the Gaia's evolutionary history (Reddy and Pereira [64], Pereira [51]).

2. Evolution of conscious life and Subject–Object Model (SOM) of consciousness

From the time of inception of the science of consciousness there has been a lot of debate on consciousness being a phenomenal property or epiphenomenal property. But for our present purpose we embrace the latter possibility to understand the emergence and evolution of consciousness across wide living spectra; from unicellular systems to a complex human system. While investigating the phenomenon of consciousness in humans, it is inevitable for science to come across the question of the presence of consciousness in other living systems. In case, if other living systems are confronted with consciousness then how different is it to humans? Humans as a species occupying the premier position in the evolutionary chart developed various advanced and complex mechanisms for functional and survival purposes. Though most of the characteristics developed looks like survival tools, some have evolutionary advantages over the others. This is where the subjective aspect of consciousness comes into picture.

Since a human species involve an evolved biological system with consciousness in its most complex form, it may not be the suitable subject for studying the evolution of consciousness. Hence, the easier way would be to try and study simpler systems first and then relate different aspects observed in those systems to that of humans. But science has failed in recent times to understand consciousness in other non-human systems because it set the criteria from human perspective of consciousness. This is where the SOM of consciousness plays a role (Reddy [59]). It bases the level of consciousness of a living system on the degree of subjectivity it would naturally develop driven by various parameters like the morphological evolution and complexity etc. (Cleeremans [6], Zeman [85], Reddy [60], Reddy and Pereira [52,60–63]). From this perspective, consciousness is an emergent property that is ubiquitous to all the biological matter but to varying levels and degrees.

In general, the possibility of making a conscious choice could result from two different aspects; one the physical structure (or the related processes) and the other, subjective experience of one's existence and happenings. If a system of physical structures is conscious of making choices then it gives edge over errors while adapting to the environment and also during system malfunctioning. Development of self-feeding mechanisms and emergency pathways increase the chances of survival, and any biological structure having a few such characteristics can be treated as conscious in a sense. From this perspective, system components with self-reflexive, self-feeding and self-organizing properties are conscious structures. Hence all biological structures that make up a functional system are conscious structures; because they are aware of their own state of functioning and also can interact with surroundings and respond accordingly. A conscious system on the other hand is a complex functional system developed by the organization of different conscious structures. For example, all the organelles inside the cell are conscious structures, because they are conscious of their respective functions; and cell as a whole, on the other hand is a conscious system. If the combination of different systems performing various functional tasks is complex enough to host and support a higher order qualitative property like subjective awareness, then a conscious choice of different quality emerges in a system. Any such system can be termed as conscious being. This way consciousness appears as just a reflexive behaviour (Peters [54]) in simpler systems and evolves to the state of subjective awareness in complex systems.

The extent of subjective aspect of consciousness developing in a system would in turn depend on factors like the degrees of freedom in various informational pathways of the system, self-organizing capacity associated with the complex pathways of the system (that would result in the lowest entropy), self-sustaining and other self-feeding mechanisms and global communication network etc. (Edelman and Tonon [12], Cleeremans [6], Greenfield and Collins [21], Tononi [76], Hankey [28,29], Webb and Graziano [81], Oizumi et al. [48], Tsuchiya et al. [78]). For example, with increased morphological complexity of the system, the heightened functioning is resultant of factors such as quickest feeding networks, minimal resistance in the wide global communication networking and maximum optimization of functional pathways etc. Such necessity calls for the emergence of a higher order property in the system which can subjectively monitor all these aspects. Consequently, the index for the proper functioning of the system would be directly related to such qualitative property (Greenfield and Collins [21], Tononi [76]). This theory explains how and why different living systems with varying complexity (morphologically and functionally) should have different levels and degrees of consciousness. This idea also justifies why lower forms of life are having a lower degrees of consciousness and the associated subtle experience of life.

3. Emergence of proto-consciousness in the microbial world

The SOM of consciousness defines the progression and incorporation of consciousness from inanimate (physical and chemical) matter to animate (biological) matter with the development of structures that support the underlying mechanism of conscious behaviour. This model also supports the Lamarckian model of evolution – *Theory of Inheritance of Acquired Characteristics* (Burkhardt [5]). The Orch-OR theory penned by Hameroff and Penrose [26], claims that tubulin proteins of the cytoskeleton have the possibility of evoking consciousness in the brain. Along with Bandyopadhyay coherence (BC) (Sahu et al. [66,67]), Orch-OR theory provides a robust support for this progression, but it needs to be extrapolated to be understood in primitive cytoskeletal structures. The evolution of the cytoskeleton and appearance of microtubules in the evolving microorganisms therefore supports the underlying mechanisms of the evolving quantum consciousness within the microbial community of the pre-Cambrian period (Hameroff [23]). According to the Orch-OR theory, quantum based consciousness is computed in microtubules present in nerve cells but whether they emerge in all cells has yet to be proven. Here, we hypothesis that quantum consciousness should originate 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 a living system to feel and understand its own existence based on the feedback resulting from different perceptive abilities, which also gives them a prospect to behave as per will (Pereira [50]). Hence, this form of consciousness should be ubiquitous to all biological systems and forms the fundamental basis by which they function, thrive and survive.

Evolutionary studies of the microbial world have been revealing an array of information which can be utilized to understand how these microorganisms survive and secure themselves in their world. Search for a common ancestor (LUCA – Last Universal Common Ancestor) still prevails but the use of phylogenetic relationships is helping us narrow down this search considerably (Glansdorff et al. [20], Boeckmann et al. [3]). As quoted above one possible advantage of consciousness for natural selection is the ability to make choices (Stevens [74]). It is only through the consensual regularities of consciousness and observed behaviours in various communities that we would come to know their world and discover their natural abilities and characteristic features. Social behaviours observed in different families of microorganisms either fossilized or currently surviving species have also helped answer several questions in relation to the possible emergence of conscious and intelligent decisions in the absence of neural systems. The evolution of the cytoskeleton within the classes of microorganisms is a key to understanding the growing consciousness among these classes and can be understood by the behaviours observed within these groups. As previously discussed, behaviour can act as a tool to quantify and understand the levels of conscious life in these living systems. Hence, our present hypothesis is based on combination of the SOM, the evolutionary traits of the cytoskeleton, conscious social behaviours in the microbial world and the quantum mechanisms that supports the emergence of consciousness in the world of microorganisms.

In cells of all domains of life (archaea, bacteria, eukaryotes) a cytoskeleton is found which is composed of similar proteins. However, the structure, function and dynamic behaviour of the cytoskeleton can be very different, depending on organism and cell type (Wickstead and Gull [83]). The cytoskeleton; a key structure supporting the Orch-OR theory, has always been considered as a unique feature to eukaryotes, which changed with the discovery that bacteria too possess homologues of both tubulin (de Boer et al. [9], RayChaudhuri and Park [58], Mukherjee et al. [44]) and actin (Bork et al. [2]). All tubulins are known to have evolved from a common ancestor, which resembles the protein FtsZ (Erickson [14,15], Pilhofer et al. [56]). The cytoskeleton as we know is composed of proteins that can form longitudinal fibres in all organisms made up of tubulin-like proteins; such as tubulin in eukaryotes and FtsZ, TubZ, RepX in prokaryotes, and actin-like proteins; that are actin in eukaryotes and MreB, FtsA in prokaryotes, and other intermediate filaments, found in eukaryotes; like lamins, keratins, vimentin, neurofilaments, desmin (Gunning et al. [22]).

Crenactin; an archaeal actin homologue, which is closely related to its eukaryotic form was discovered in a *Crenarcheaota Pyrobaculum calidifontis* as helical structures that form the cytoskeleton in these archaea bacteria involved in cytokinesis (Ettema et al. [16], Izore et al. [31]). FtsZ contains 4 main domains and was observed in the crystal structure of FtsZ from archaea *Methanococcus jannaschii* (Lowe and Amos [40]). Bacterial FtsZs are 40–50% identical in sequence even across very divergent species, while archaeal FtsZs show a similar level of identity to each other and to bacterial FtsZs (Vaughan et al. [80]). For MreB and actin, bacterial MreBs are generally about 40% identical in sequence even across diverse species; similar to FtsZ (Erickson [15]). Though FtsZ is a respective homolog of tubulin, the evolutionary distance between the two proteins is substantial and hence it has been suggested that an undiscovered species of bacteria or archaea could hold the evolutionary precursor of tubulin that could determine the true evolution of this protein. FtsZ could therefore be considered as the precursor for quantum computation resulting in the origination of quantum proto-consciousness (Barlow [1], Hameroff et al. [25]). This idea is supported by several theoretical models and simulations which suggest that conformational states of tubulins within microtubular lattices are influenced by quantum events (Hameroff and Watt [27], Tuszynski et al. [79], Pitkanen [57], Kukuljan [36], Faber et al. [18]). The presence of a primitive form of cytoskeleton and other adaptable mechanisms in this group of microorganisms may have been the inception of expression via quantum computed proto-consciousness. Quantum computation in these structures may seem possible because of the adaptive intelligence demonstrated by these microorganisms.

Archae were the first organisms to demonstrate cooperative conscious behaviours in microbial mats which originated during the environmental transition period from anaerobic to aerobic form; a beginning of species diversity (Lyons and Kolter [41]). Adaptive behaviour is another form of social behaviour that is used by these microbial systems to adjust to a situation (Staddon [72], Sieb [70]). Archaeal microorganisms are flagellated organisms, unlike the cyanobacteria and these structures are a well-built feature used by these organisms to adapt and survive. Two archaeal systems, *Methanocaldococcus jannaschii* and *Methanocaldococcus villosus*, were tested to be the fastest organisms in speed measured as bodies per second (bps) based on their swimming potentials. These flagellated archaeal organisms demonstrate speeds at close to 400 and 500 bps which are high speeds when compared to a bacteria like *E. coli* or a fast runnable animal such as cheetah; which moves at a speed of 20 bps (Herzog and Wirth [30]).

Archaea is a highly conserved primitive group of bacteria which were earlier found only in extreme environments (DeLong [10], Nicks and Rahn-Lee [47]). They constitute primitive forms of extremophiles; where each species develop certain characteristics (either physically or functionally) to thrive in extreme environments (Stetter [73], Reed et al. [65]). For example, *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. [11]) to maintain optimal water activity within the cell and at cell surface (Bolhuis et al. [4]).

Since bacterial FtsZs show a similar level of identity to each other and to archaeal FtsZs (Vaughan et al. [80]), it would be interesting to look at intelligent behaviours exhibited in by these organisms as well. Bacterial intelligence is a form of minimal intelligence, which provides the 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. Jenkins and team isolated two tubulin-like genes (bacterial tubulin a (BtubA) and bacterial tubulin b (BtubB)) from bacteria of the genus *Prosthecobacter* (Division Verrucomicrobia). These *Prosthecobacter* tubulins were monomeric and unlike eukaryotic tubulins, but forms dimmers (Jenkins et al. [33]). In contrast to all other prokaryotic tubulins, BtubA/BtubB can form tubules by 5 proto filaments instead of 13, as observed in eukaryotes (Pilhofer et al. [55]) and there is enough proof that both may have been acquired by horizontal gene transfer from eukaryotes confirming that the most likely ancestor of eukaryotic tubulins as of now remains to be FtsZ (Jékely [32]). 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 [77]).

Microorganisms demonstrate the beginnings of primitive mental processes such as perception, learning and emotions where the organism is only aware of the environment and chooses ways to adapt (Crespi [8]). This growth in complexity is clearly visible in the SOM that explains the growing mental processes from primitive single celled organisms to complex multi-cellular organisms i.e. from cell to neuron and the evolving cytoskeleton supporting complex quantum computations. Bio-film 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. [19], Majumdar [42]). Bacterial bio-films are structures created due to colonization, wherein the bacterium carries out its duties in a cooperative manner by means of quorum sensing (Majumdar [42]). Bio-films are also created for shelter and procurement of food by means of cooperative behaviour such as foraging (Nadell et al. [45]). *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 swarmers as a means of survival (England and Gober [13]). Heterocyst 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. [86]).

Therefore 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. [43]). Slime moulds or protists are the best examples that demonstrate behaviour similar to neurologically sophisticated organisms e.g. *Physarum polycephalum* (Latty and Beekman [38]). *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. [46]). Amoeba has no structures for reception of stimuli but the protoplasm responds to a stimulus, which gives it the ability to perceive and recognize its own kind and engage in cooperative behaviour. 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 et al. [71]). Generation of a conscious moment in paramecia is depicted as a behavioural response to a stimulus which helps the organism understand its surroundings (Jennings [34], Hameroff [24]). Anaesthetics are known to act on microtubules, the cytoskeleton polymers of the protein tubulin inside brain neurons and therefore affect consciousness and memory (Pan et al. [49]). Similarly anaesthetic effects were also observed in cytoplasmic streaming inside slime moulds which wholly depends on the dynamics of the cytoskeletal proteins (Perouansky [53], Craddock et al. [7]). Therefore evolution of the cytoskeleton is a key step to propagation of consciousness which was more of a survival advantage which could provide support in anticipating threats and strategic opportunities as key genes for the brain evolved much before (Wickramasinghe [82]).

4. Conclusion

Sentience or conscious behaviour is prevalent in all three domains of the unicellular kingdom. Though it is in lower degrees in comparison to the living systems that developed neural networks; by the division of labour in cells it propagates and attains a higher state, as observed in higher organisms. Ancestral precursors in the evolution of the cytoskeleton wherein, quantum coherence would have been an intrinsic property of prokaryotic FtsZ and MreB, have helped propagate consciousness in primitive cells. The growth in complexity of intelligence, cytoskeletal system and adaptive behaviours are key to evolution, and thus supports the progression of the Lamarckian theory of evolution driven by quantum mediated proto-consciousness to consciousness as described in the SOM of consciousness. In nature, new species have arisen through variation and selection following the laws of nature with those varying in conformity with the environment. In a cell or a group of cells e.g. a microbial mat or a developing embryo, the cells always demonstrate an involuntary behaviour supported through genetic makeup which appears as a reflex and may not be due to consciousness per se. But the reason to behave and adapt is the act of learning which may originate through consciousness; for a cell needs to be aware for it to adapt and perceive, and therefore even though perception and consciousness are two qualitatively distinct properties, they complement each other.

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