A comparative approach to determining the biological and physical bases for consciousness

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Introduction:

A critical gap in our understanding of ourselves and other animals is how the conscious feeling of self-awareness arises from the brain. In a number of experimental animal systems and even in humans, the neural basis of sensory transduction, sensory coding, action selection, movement generation, learning, and memory, is already understood at a deep level in terms of neuronal interactions through electrical and chemical interactions. Even the neurochemical mechanisms underlying emotional states such as fear and affiliation have been addressed, with known neurohormones acting on receptors in particular brain areas. However, there is no accepted causal model for understanding how such coordinated electrochemical interactions create the qualia of sensory perception, the conscious thoughts associated decision-making, or the feelings associated with moods and emotions.

The lack of understanding of the physical underpinnings of consciousness is not due to insufficient interest. However, with a few important exceptions (Crick and Koch, 1990; Chalmers 1995,1996; Dehaene and Changeux 2011; Koch et al. 2016), the field of neuroscience has almost abandoned the effort, labeling it the “hard problem” and retreating to solve more tractable problems. Indeed, scientists who propose new theories to explain consciousness are often dismissed out of hand, leaving it to philosophers to explain consciousness (Dennett 1991). Yet, the grand question persists: What are the physical causes of conscious perception?

Determining the biological and physical processes that enable an organism to be self-aware is a valid scientific endeavor that requires perspectives and methods across many levels of biological and physical investigation. Furthermore, it is likely that consciousness arose through natural evolutionary processes and confers a selective advantage upon organisms that have it. Darwin himself noted the importance of a comparative approach to emotional states (Darwin 1872). Therefore, we outline challenges and opportunities to address the crucial issue of how and which physical forces and biological structures cause the experience of the world that we as sentient beings share, and propose a comparative approach to help determine the physical mechanisms that cause conscious self-awareness.

The implications of this research could be profound. For example, understanding the physical basis of consciousness could lead to a revolutionary understanding of altered states of consciousness including some forms of mental illness. If the physical cause of conscious self-awareness is uncovered, it could potentially be replicated, leading to artificial entities that exhibit awareness, so-called thinking machines. It could also uncover that self-awareness is present in organisms or even eusocial groups of organisms that we previously did not appreciate as having such a property. This could have implications for ethical treatment of non-humans and for the ethics of human social structures.

The goal of this white paper is to catalyze discussion and motivate a cadre of diverse researchers from across the breadth of relevant disciplines within and external to biology to consider the opportunities of investing their efforts on this intensely challenging and important topic.

Key Barriers

One of the major barriers for determining the physical basis of conscious self-awareness is defining what it is (Overgaard 2017). There has been such intense disagreement about the nature of consciousness that a recent challenge was made to researchers to propose a testable hypothesis and accept the outcome of a large-scale experiment that might disprove it (Reardon 2019). However, even the proposed experiments do not bridge the key question of the nature of the physical basis for consciousness, relying instead on tests of critical locations in the brain and testing how the brain processes information as proxies for the qualitative sensation of consciousness.

Another key barrier is the inability to produce a workable model that can account for the phenomena of consciousness from known physical properties. Prior to Galvani, models of nervous system function relied on the observable fluids. Galvani related bioelectricity to the movement of muscles (Whittaker 1951), but it took Volta to realize that electricity is a physical property that could be generated by inorganic materials (Giuliano 2003). It was not until electrical potentials could be measured that electrical signaling in the nervous system could be quantified and Sherrington could do experiments that led to the notion of reflexes mediated by synapses between neurons. Similarly, it could not be established that electrical signals were carried by individual cells until Cajal used Golgi stain to expand the neuron doctrine (Finger 1994). Each step in the development of theories of brain function required new techniques to reveal the nature of the components that work together. It is possible that we are now at a point in history equivalent to the time before the discovery of the nature of electricity or the development of histological techniques to visualize neurons; we may need a revolutionary conceptual or technological breakthrough in the ability to understand and measure the relationship of known physical forces and matter to as yet unmeasurable forces or quantities.

Why now?

Technological developments have accelerated in recent years. We now have new and emerging methods for recording and stimulating neuronal activity. There are clear hallmarks of conscious activity from EEG and fMRI recordings that allow us to determine if an individual is conscious even if they are exhibiting locked-in syndrome, coma, or persistent vegetative state (Gawryluk et al. 2010; Gosseries et al. 2014). For example, EEG recordings of brain waves, which are caused by coordinated neural activity, exhibit characteristic patterns when people are awake or asleep, attending to something in the environment or meditating. Furthermore, thanks in large part to the BRAIN initiative (Kandel et al. 2013) and research institutes such as HHMI's Janelia Farm Research Campus and the Allen Brain Institute, new technology is now available for mapping and manipulating neuronal activity at the single cell level as well as determining the concentrations neurotransmitters in multiple brain locations in real time. Systems biology methods (including genomics, transcriptomics, epigenomics, metabolomics, and structural biology) have advanced to the stage where we can begin to quantify and catalog the molecular ingredients that are coincident with recognizable self-awareness. Moreover, computational power has increased, enabling massive enhancements in machine learning to find patterns in signals (Alber et al. 2019) and large-scale computational simulations to mimic brain activity (Farisco et al. 2018). Therefore, the ability to catalog the parts of the brain, determine their interactions, and computationally model the results has never been greater.

There is also a growing appreciation for the value of a comparative approach. Much of neuroscience has relied on a small number of "model" species (Katz 2016). That approach has enabled tremendous advances in understanding the details of neural processing in these species. However, tools such as CRISPR-Cas9 are now allowing genetic tools to be applied to a wider diversity of organisms. Determining the generalities of brain processing ultimately requires comparing the features of species that possess conscious self-awareness to those that demonstrably do not. For example, it seems likely that octopuses have an awareness of the world based on their behavior, such as the ability to learn from observation (Mather 2008). The most recent common ancestor of molluscs and mammals is at the base of Bilateria, a simple worm-like creature, and was not likely to have had conscious awareness, suggesting that consciousness evolved independently, or at least increased dramatically, in humans and octopuses. Since octopuses have as many neurons as mice, it could be that the number of neurons is a prerequisite for consciousness, leading to predictions about whether other species would exhibit that property. It would be useful to test this prediction by explicitly looking for hallmarks of consciousness in species that one would predict are not conscious.

How does tackling this problem reintegrate biology?

Transformative advances span biological scales that link molecular properties to anatomy, physiology, behavior and emotion. Missing in this synthesis is possibly the final step to self-awareness. Considering newly available technologies, a re-imagining of the grand existential Descartian conclusion: "I think, therefore I am" has the power to motivate and mobilize an entire generation of educators and scientists whose disciplines span the entire range of biological complexity -- reintegrating biology.

An integrated approach to addressing the question of consciousness will need broad participation of researchers in fields from physics to cognitive science. Neuroscience alone has been stymied by this challenge. It has been said that perhaps the human brain is not capable of understanding itself. Possibly, machine learning is needed to see the patterns in the data that our own awareness cannot fathom. Data scientists will be needed to provide a structured basis for this deep search of correlates of consciousness. Developmental scientists, cognitive scientists, geneticists, all have roles to play in this massive undertaking. Recognition of the evolutionary history and theoretical selection pressures that led to the evolution of self-awareness need to be included in the discussion. Importantly, much as the discovery of bioelectricity in frogs' legs and action potential transmission in squid axons transformed our understanding of neuronal signaling, detailed comparative studies of tractable systems can set the stage for the discovery of new physical or chemical phenomena that provide the elusive mechanistic link between physical properties and the perception of the world.

A Path Forward:

The challenges described above are immense, but progress in this realm is critical to our understanding of humanity and the world around us. We need to reinvigorate searches for models that account for hallmarks of consciousness across the phylogeny (Edelman et al. 2005). A comparative approach will enable us to distinguish features that are common to systems that exhibit these hallmarks and thus provide a basis to suggest a minimal set of requirements for consciousness (Griffin 2000, Owen and Guta 2019).

It is important to acknowledge that consciousness or self-awareness is not likely to be a unitary phenomenon. We know from our own experience that there are different levels of conscious perception even over the course of a day and as a result of drug interventions, disease, or injury. Furthermore, different species are not likely to have the same experience of the world. We would probably not recognize the world through the brain of an octopus or a mouse for that matter. It is critically important to determine whether consciousness arises through a single mechanism that exhibits differences of degree, or whether there are fundamentally different mechanisms to achieve a state of self-awareness. If there are different mechanisms, then it could point to the core similarities to achieve this state, whereas if independent evolution of consciousness converged on a single mechanism, it would be strong evidence for an important universal truth.

We therefore suggest identifying species that exhibit hallmarks of consciousness through brain activity or behavior and species that do not have these features (Edelman et al. 2005). A meta-analysis of features that are shared by so-called conscious species and non-conscious species could yield clues to the molecular, anatomical organization, or activity patterns that lead to self-awareness. Those traits could then be manipulated to look for changes in hallmarks of consciousness including behavior. Thus, a comparative approach across the phylogeny is essential for resolving this unresolved fundamental mystery. It is exciting to think that we may be on the cusp of the next era of our understanding of the brain and how it functions.

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