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Review Article

Current Status of Consciousness Research from the Neuroscience Perspective

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Abstract

In this paper, an outline of the current status of research in the study of consciousness as a neurobiological phenomenon is presented. Consciousness studies forms a very vast interdisciplinary field, with more than hundreds of papers published each year in the scientific databases. The contributors come from as varied academic backgrounds as the humanities and the sciences. To begin with, a brief history of consciousness studies starting from its inception in philosophy upto its present state of evolution in the sciences is summarized. The different tools used such as neuroimaging technologies (e.g. fMRI, PET), neuroelectric recording (e.g. EEG) and neuromagnetic recording (e.g. MEG) are described along with all their respective strengths and drawbacks. The quest for the Neural Correlates of Consciousness is considered the holy grail of most consciousness research today, but there are strong reasons to doubt whether such an approach can actually provide a satisfactory answer to the question that scientists and philosophers alike are seeking after, which is an explanation for the first-person sensory experience of the world, otherwise referred to as qualia. A few of the many proposed theories that offer such an explanation are listed as well as the future directions which neuroscience is likely to take the field in the coming decades is mused upon.

Keywords: Neural Correlates of Consciousness; Qualia; Neuroimaging; Electroencephalography

Introduction

Like most other human endeavors that employ the scientific method, the study of consciousness too can trace its origins to Philosophy [1]. In the Western tradition, philosophers mused on the subject for no less than a millennium and in the Eastern tradition its roots stretch back much further. In striking contrast, its only in the last century or so that psychologists included consciousness as one of their central themes for investigation, while Neuroscientists, Computer scientists, Physicists and Mathematicians are the most recent entrants on the scene over the past few decades [2,3].

A Brief history of modern consciousness studies

In their pivotal 1990 paper, Francis Crick and Christoff Koch made the following remark, “Most work in Cognitive Neuroscience makes no reference to consciousness” [4]. In the subsequent two decades, the explosion of interest in the neuroscientific study of consciousness has drastically changed that outlook. It is today a rich multidisciplinary subject, receiving a steady stream of contributions from psychologists, philosophers, computer scientists, clinicians, neuroscientists, physicists and mathematicians. The grand technological strides made in imaging and recording brain activity in a non-invasive manner in the late eighties and early nineties is the major reason for this sudden frog leap from obscurity to popularity. But it can also be partly attributed to the string of predictive and explanatory successes of Physics, take for example, the fact that we can correctly predict the future positions of heavenly bodies based on the knowledge of their present positions and trajectories. This apparent mastery over the vagaries of our mortal existence lends us hope and confidence that perhaps one day even consciousness can be understood from the framework of simple physical principles [5]. In the 1950s, a series of rapid developments led to the foundation of a new field called Cognitive Science – the science that studies how thought processes occur in the mind. These include Norbert Wiener’s Cybernetics, Claude Shannon’s Information Theory, the invention of Turing Machine, Formulation of Church-Turing Thesis, Invention of large electronic

Computer machines, Von Neuman's invention of Programmability of computers [6]. It ushered in a new way of thinking about man, that he is a programmable machine, and that while the brain acts as hardware, the mind acts as software. Building on these developments, David Marr published his landmark book (posthumously), titled 'Vision' in 1982 which compares the functioning of the brain to that of any other Computational System [7]. The work helped lay the foundations for the field of Computational Neuroscience. In it, Marr describes the essential requisites for any system, neural or otherwise to be computational, though his primary focus was on the working of the visual system of the brain. First, there must be a goal or a target to be reached (i.e. a computation). Next, there should be an overall plan or rule based, systematic approach to reach that goal (i.e. an algorithm). Each input step in that plan must correspond to a particular output result in the system (i.e. a representation). Finally, there must exist a process which links all of the steps together in a sequence (i.e. a mechanism). An example of a simple computational system from physics is a Spring-Mass System. It consists of an elastic spring which is fixed on one end and loaded with a weight on the other. Being elastic, the spring obeys Hooke's Law, which states that the extension x of a spring is directly proportional to the weight w of the load applied onto it. Such a system can be used to determine the combined weight of two separate loads, each contributing an extension effect on the spring. In terms of the four-fold scheme, we can write down the following to describe the computational process:

1. **Computation:** $w_{net} = w_1 + w_2$
2. **Algorithm:** Hooke's Law: $F = k.x$; $w_1 = k.x_1$; $w_2 = k.x_2$
3. **Representation:** displacement x represents weight w
4. **Mechanism:** spring, mass, gravity

In the context of consciousness, however, the computational paradigm utterly fails because while the spring-mass system does indeed perform a computation, namely that of addition of weights of two loads, it is by no means conscious of doing so. In other words, a system that is computational in nature is not a sufficient reason for attributing consciousness to it. So, by merely figuring out in elaborate detail the algorithms that underly the functioning of the brain, there is no assurance that we in turn will draw any nearer to an understanding of the nature of consciousness itself. In the closing decade of the 20th century, the philosophers John Searle and David Chalmers helped bring about a climax in interest of the scientific community in consciousness studies [1]. John Searle put forward the doctrine of biological naturalism which holds that all mental phenomena can be causally explained based upon biological processes happening at the level of the neurons and synapses in the brain [8,9,10]. He also listed and simultaneously offered solutions to the philosophical obstacles that hinder progress in the field [11]. David Chalmers succinctly identified two sets of problems when it comes to scientifically studying consciousness [12,13]. One set came to be referred to as the hard problem of consciousness which aims at understanding how and why it is that some internal brain states are felt states, such as heat or pain, rather than unfelt states, as in a thermostat or a toaster. In his own words, "why should physical processing give rise to a rich inner life at all?" The other set of problems is called the easy problems of consciousness. These include (1) the ability to discriminate, categorize, and react to environmental stimuli; (2) the integration of information by a cognitive system; (3) the reportability of mental states; the ability of a system to access its own internal states; the focus of attention; (4) the control of behavior; (5) difference between wakefulness and sleep. Regardless of whether a neuroscientist is working on the hard or easy problems, the ultimate aim of all consciousness research is the same and that is to connect the 3rd person objective data (quantitative data) with 1st person subjective data (verbal reporting), i.e., to find the causal link between the occurrence of brain events (that are measurable) to the conscious experiences (contents of consciousness that are reportable) [3].

What is consciousness?

There is little consensus in the scientific community on a suitable definition of consciousness [2,3,14]. This pitfall isn't as bad as it seems since many of the fundamental quantities in physics are not well defined either. For example, it isn't possible to define such things as electricity or matter or space or time and yet these entities are undeniably perceivable to the human mind. The lack of a working definition for space or time or matter or electricity does not in any way pose a hindrance to the physicist when trying understand the grandeurs of nature. It is therefore, reasonable to assume consciousness to belong to that same category of primitives which cannot be understood from anything simpler than itself. An operational definition of consciousness however, can help give direction to studying it scientifically. A few such definitions are as follows: "consciousness is the dynamic, integrated, multimodal mental process entailed by physical events occurring in the forebrain" [14]; "consciousness is what disappears when we fall into a dreamless sleep and what returns the next morning when we wake up" [3]; "consciousness is the awake state in which we have the experiences about which we can report at free will or request" [2].

A pragmatically relatable definition is "consciousness is the awareness at any given instant, of events happening inside the mind like thoughts, feelings, perceptions and of the objects encountered in the environment that cause sights, sounds, smells, tastes and touch".

Why do we have Consciousness?

There are many theories offered to help explain why we have consciousness in the first place. Why couldn't we just be automatons or philosophical zombies? Why do we need to feel at all in response to things that happen in the environment around us? According to Thomas Huxley, consciousness is a byproduct of neural activity that itself has no effect upon neural activity, for example, the rumbling noise made by a motor car engine has no effect upon its motion [15]. This school of opinion in the philosophy of mind is called epiphenomenalism, according to which a physical state can give rise to a mental state but not vice versa [16]. Another theory put forward by Feinberg and Mallatt, holds that consciousness is purely an accidental outcome of the increase in the size of the brain and the restructuring of the cortex, bearing no specific purpose whatsoever (e.g. the blind-spot of the eye's visual field has no purpose, but is a result of the way the retina is wired up) [17]. According to William James, the possession of consciousness confers a survival advantage for the animal in its environment [18]. That is, if the brain has supposedly evolved over millions of years by means natural selection, then consciousness may be an adaptation that increased the fitness of the organism, allowing it to distinguish between what is real from what is apparent (e.g. a desert animal would conserve energy if it could consciously reflect upon its own perception when trying to distinguish between water and a mirage).

Theories/Models of Consciousness

Though we lack a true understanding of what consciousness is and why we even have it in the first place, there is no dearth in the literature for theories that models it. Listed below are a few of the many proposals that attempt to explain the working mechanisms of consciousness. A description of each theory, however, is beyond the scope of this paper.

1. Global Workspace Theory [19,20,21,22]
2. Phenomenal and Access Consciousness Theory [23]
3. 1st and Higher Order Representation Theory [24]
4. Information Integration Theory [25]
5. Consciousness State Space Theory [26]
6. Quantum Theories of Consciousness
    a. Holonomic brain theory – Karl Pribram and David Bohm [27]
    b. Orch-OR theory – Stuart Hammeroff and Roger Penrose [28]

Strategies for studying Consciousness

There are three distinct approaches to the scientific study of consciousness [1,14]. They are namely, the direct approach otherwise referred to as the phenomenological or subjective approach, then there is the indirect approach otherwise referred to as the biological or objective approach. Finally, there is the combined approach which makes use of both the direct and indirect methods. In the direct approach, the subject is required to report on his/her experiences when presented with a particular stimulus. For example, visual illusions such as the Necker cube can be perceived in two different orientations. By the mere act of blinking, an observer can cause a switch or flip in the perception of the cube's orientation, and verbal reporting is the only means of accessing this sort of information. In the indirect approach, the subject is presented with multiple stimuli and is required to choose between alternatives. An example of this approach is the Forced Choice Task. Emadi and Esteky trained two monkeys to make a forced choice between making an eye saccade towards a visual stimulus (image of a body or image of a chair) [29]. Each time a saccade was made towards the target (body), the inferior temporal cortex showed increased activity.

Binding Problem

At the heart and core of consciousness studies lies the binding problem. It also acts as the meeting point of neuroscience, cognitive science and philosophy of mind [30]. The brain has purportedly over millions of years of evolution somehow found a way to solve this difficult computational problem and we are left with the scientific challenge of figuring out how it did so. Solving this problem is equivalent to understanding qualia, i.e. the subjective experience of the world, or solving the hard problem of consciousness itself. The visual system can be best used to understand the complexity of the binding problem. In a given visual scene, different features like faces, colors, motion, shape, orientation, edges etc. are processed in different regions of the brain. For example, when we look at an object in the environment, say an apple, its color, size, location, edges and shape are processed by different areas of the occipital, temporal and parietal cortices and yet the subjective visual experience is unitary in nature and not a series of colors, edges, shapes and positions. So how does the brain keep track of processing different kinds of information about an object and puts all of that back together again so that the unity of conscious experience is made possible? To make the binding problem more tractable, it has been conveniently broken down into two smaller component problems, namely, the segregation problem and the combination problem [31]. The segregation problem deals with how the brain breaks up different sensory aspects of a given object in the environment and processes them through separate neuroanatomical pathways. The combination problem deals with how the brain combines the information processed in the different neuroanatomical pathways so that the person is able to have a unitary experience of that object and not a collection of shapes, colors, edges etc. More importantly, where in the brain does such a combination happen? When viewing a scene containing a red triangle and a green rectangle, some color processing neurons fire in response to the red color while others fire in response to the green color. Similarly, some shape processing neurons fire in response to the triangle shape while others to the rectangle shape. So, the binding problem in this case is concerned with the issue of how the brain correctly pairs color and shape, i.e. red goes with triangle and green goes with rectangle and not red with rectangle and green with triangle [32,33]. Again, several theories including computational ones have been proposed but the two most popular with empirical backing are Synchronization Theory [34] and Feature Integration Theory [35]. According to synchronization theory, binding happens when the neurons of the cortex fire synchronously, typically in the gamma range of 40 Hz. According to feature integration theory, binding happens by means of common location tags of different features. The literature on the various theories that offer to solve the binding problem, however, is too extensive to cover here.

Quantitative assessment of consciousness

Clinical practice follows a highly practical approach to the study of consciousness. There is simply no room for either philosophy or psychology since the principal goal is the treatment of disease and to avoid a potential misdiagnosis while doing so. This point is especially important to neurologists and anesthesiologists. The former group of medical professionals often encounter patients who have fallen into a state of unresponsiveness following a brain injury. There are few guiding principles beyond some conventional clinical methods for assessing the level of consciousness in a brain injured patient. Infact an objective measure of consciousness which is independent of the subject's ability to interact with the external environment has hitherto eluded grasp. Quantifying consciousness by means of a reliable neuro-marker would help solve the physician's dilemma of distinguishing between various disorders of consciousness like locked in syndrome, minimally conscious state, persistent vegetative state, chronic coma and brain death. The various neuro-markers that have been developed in recent times which convey some idea on the level of consciousness are listed below. Further refinements in the years to come towards a gold standard neuro-marker of consciousness will prove an invaluable tool to the field of medical diagnostics [36].

1. Lempel-Ziv Complexity Index [37]
2. Perturbational Complexity Index (PCI) [38]
3. Bispectral Index (BIS) [39]
4. Gamma band (30-45 Hz) on EEG [40]
5. P300 Event Related Potential [41]

Tools used in consciousness studies

Several tools have been developed over the last century that have increased our understanding of brain function in general and consciousness in particular. They can be broadly divided into neuroimaging, neuroelectric and neuromagnetic technologies. Neuroimaging technologies include functional Magnetic Resonance Imaging (fMRI) and Positron Emission Tomography (PET), neuroelectric technologies include Deep Brain Electrical Stimulation (DBES) and Electroencephalography (EEG), neuromagnetic technologies include Magnetoencephalography (MEG) and Transcranial Magnetic Stimulation (TMS).

fMRI [42]

This rather bulky and noisy device generates a magnetic field that can measure changes in blood flow in the brain i.e. hemodynamic changes. If a particular brain area is working hard to accomplish a certain behavior, it consumes more oxygenated blood, producing a dip in the fMRI signal which is also called the BOLD signal. These signals are in turn converted into an image of the brain. The specific advantage of this technology is that it has made it possible to non-invasively identify the neural correlates of cognitive processes like memory, learning and attention. Despite having excellent spatial resolution, it cannot be used to study language processes, because the head should be held absolutely still during image capturing. It additionally, has poor temporal resolution.

PET [42]

Very similar to an fMRI machine, except that it creates images of the brain by tracking the disintegration of injected radioactive molecules like radio labelled glucose or dopamine or oxygen. It achieves this by identifying which regions of the brain are the most metabolically active, thus, revealing connected regions. It carries the advantage over fMRI that it can be used to study language processes because faithful image capturing is more or less independent of head movements. It also has excellent spatial resolution. However, like fMRI it too has the disadvantage of poor temporal resolution. Additionally, it is an invasive approach since it makes use of radioactive substances.

EEG [42]

This device measures the electrical activity of the brain by means of placement of electrodes on the scalp in a pre-specified manner. The derivatives of EEG include Evoked Potentials (Visual EP, Auditory EP, Somatosensory EP) and Event Related Potentials (P300 – Oddball paradigm). The advantages of using EEG is that it has excellent temporal resolution and is non-invasive. The disadvantage however, is poor spatial resolution.

DBES

Deep brain electrical stimulation involves implanting an electrode in a specific region of the brain (usually the thalamus), which passes a current to alters the activity of its neural circuits. Chudy., et al. of the University of Zagreb, have successfully used DBS to help in the recovery of consciousness in patients in Minimally Conscious State (MCS) and Vegetative State (VS) [43].

MEG

In this technique, brain activity is mapped by recording magnetic fields produced by electrical currents occurring naturally in the brain, using very sensitive magnetometers (SQUIDS). Schartner., et al. demonstrated for the first time a reliable MEG measure for detecting higher states of consciousness on using psychedelic drugs (PSIL, KET, LSD) [37]. The statistical signatures that correlates with the conscious experiences of the study participants is called Lempel-Ziv Complexity Index.

TMS

Transcranial stimulation is a non-invasive procedure in which a changing magnetic field is used to induce an electric current to flow in a small targeted region of the brain based on Faraday's principle of electromagnetic induction. One TMS pulse causes neurons in the neocortex under the site of stimulation to fire. If used in the primary motor cortex, it produces muscle activity. If used on the occipital cortex, 'phosphenes' (flashes of light) might be perceived by the subject. He., *et al.* of the University of Zhejiang, have used 20 Hz Repetitive Transcranial Magnetic Stimulation (rTMS) on patients in the VS and MCS and found that there were behavioral and EEG modifications [44]. Massimini., *et al*. used TMS to generate slow waves and spindles that are characteristic of deep sleep [45].

Neural Correlates of Consciousness (NCC)

A chunk of all consciousness research consists of exploring the relationship between the perceptual experiences reported by the subjects and the activity that simultaneously takes place in their brains. The findings of these studies that attempt to correlate the neural activity in the brain to the conscious experience that they supposedly bring about are called the Neural Correlates of Consciousness (NCC). Neuroimaging technologies like fMRI and PET have made this possible. The philosopher of mind David Chalmers defines NCC as the minimal neural activations that are sufficient for a specific content of consciousness [46]. Crick and Koch defines NCC as the minimal neural mechanisms that are jointly sufficient for any one conscious precept [47]. There are essentially two types of NCC, namely, content-specific and non-content specific NCC [1]. Content-specific NCC includes neural activity in response to colors, faces, places, thoughts. A specific example is the Fusiform Face Area (FFA) which is a part of the human visual system that is specialized in facial recognition. It is located in a part of the Inferior temporal cortex (IT) called the fusiform gyrus (Brodmann area 37). Non-content specific NCC includes neural activity during the MCS, VS, comatose state, brain dead state, asleep state, awake state etc. However, the NCC approach to the study of consciousness is not without its own set of problems.

Problems with the NCC Approach:

1. NCC does not explain conscious experience (i.e. how qualia can come to be) – it only tells us what parts of the brain are predominantly active while the mind is engaged in a particular activity [1].
2. It is difficult to assess the level of consciousness using NCC in the vegetative state because the damaged brain is significantly reorganized in terms of structure and function compared to a normal brain [1].
3. It is still uncertain if the neural correlates of visual consciousness lie in the front or in the back of the brain [48]. A number of studies have shown that activity in the Prefrontal Cortex (late activations) reflects awareness of an object in the environment [49] while others suggest that this actually happens in the occipital cortex (early activations) instead [50].

4. NCC research is heavily dependent on a subject's reporting of conscious experiences, that is, consciousness gets inevitably conflated with reportability, thus, diminishing the objectivity of the results of the studies [2].

Future Challenges and Conclusion

It is difficult to prognosticate about how the field of consciousness studies as a scientific enterprise will evolve in the coming decades, particularly with the increasing diversity of its principal contributors. It is an even greater hurdle to try and assess the full scale sociological and technological impact of our ever-expanding understanding of brain function at the subcellular, cellular, network and neural systems levels. Listed below are a few of the major challenges faced and breakthroughs hoped for:

1. Development of reliable quantitative neuro-markers to assess the level of consciousness in vegetative state or coma state patients
2. Invention of mind reading and thought broadcasting technologies
3. A deeper and more fundamental understanding of the workings of brain-computer interfaces
4. Creation of consciousness in artificial systems like robots and computers
5. The complete export of the mind-body problem from the domain of philosophy into the domain of neuroscience
6. Experimentalists and theoreticians must together strive hand in hand, to convert the huge volume of collected empirical data into a coherent, self-consistent and verifiable narrative.

It may be stated with a fair degree of certainty that we as a species are headed towards a time in our history when we can finally begin to comprehend what it truly means to be human.

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