

**chapter**
15

The Neurobiology of Consciousness

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In recent years, the mystery of consciousness and its material basis has attracted scientific interest beyond the traditional field of philosophy. The neurobiological approach to consciousness aims at identifying its physico-chemical basis at the neuronal level of the brain. Electrophysiological, psychophysical, and functional imaging studies in humans and non-human animals have allowed brain scientists to narrow down on the neural substrates of consciousness and conscious perception. These findings, complemented by the development of a robust theoretical predictive framework, could eventually lead to a rational understanding of the phenomenon of consciousness.

1. The Neurobiological Approach to Consciousness

Consciousness is one of the most enigmatic features of the universe. People not only act but feel: they see, hear, smell, recall, plan for the future. These activities are associated with subjective, ineffable, immaterial feelings that are tied in some manner to the material brain. The exact nature of this relationship — the classical mind-body problem — remains elusive and the subject of heated debate. These first-hand, subjective experiences pose a daunting challenge to the scientific method that has, in many other areas, proven so immensely fruitful. Science can describe events microseconds following the Big Bang, offer an increasingly detailed account of matter and how to manipulate it, and uncover the biophysical and neurophysiological nuts and bolts of the brain and its pathologies. However, this same method

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has as yet failed to provide a satisfactory account of how first-hand, subjective experience fits into the objective, physical universe.

The brute fact of consciousness comes as a total surprise; it does not appear to follow from any phenomena in traditional physics or biology. Indeed, some modern philosophers even argue that consciousness is not logically supervenient to physics.¹ Supervenience is used to describe the relationship between higher-level and lower-level properties such that the property *X* supervenes on property *Y* if *Y* determines *X*. This implies, for example, that changing *Y* will, of necessity, change *X*. In that sense, biology is supervenient to physics. Put differently, two systems that are physically alike will also be biologically alike. Yet it is not at all clear whether two physically identical brains will have the same conscious state.

Note that it is not yet generally accepted that consciousness is a appropriate subject of scientific inquiry. A number of neuroscience textbooks provide extended details about brains over hundreds of pages yet leave out what it feels like to be the owner of such an awake brain, a remarkable omission.

People willingly concede that when it comes to nuclear physics or molecular biology, specialist knowledge is essential; but many assume that there are few relevant facts about consciousness and therefore everybody is entitled to their own theory. Nothing could be further from the truth.

There is an immense amount of relevant psychological, clinical and neuroscientific data and observations that need to be accounted for. Furthermore, the modern focus on the neuronal basis of consciousness in the brain — rather than on interminable philosophical debates — has given brain scientists tools to greatly increase our knowledge of the conscious mind.

Consciousness is a state-dependent property of certain types of complex, biological, adaptive, and highly interconnected systems. The best example of consciousness is found in a healthy and attentive human brain, e.g., the reader of this chapter. In deep sleep, consciousness ceases. Small lesions in the midbrain and thalamus can lead to a complete loss of consciousness, while destruction of circumscribed parts of the cerebral





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cortex can eliminate very specific aspects of consciousness, such as the ability to be aware of motion or to recognize faces, without a concomitant loss of vision in general.

Brain scientists are exploiting a number of empirical approaches that shed light on the neural basis of consciousness. This chapter reviews these approaches and summarizes what has been learnt.

2. What Phenomena Does Consciousness Encompass?

There are many definitions of consciousness.² A common philosophical one is “Consciousness is what it is like to be something,” such as the experience of what it feels like to smell a rose or to be in love. This what-it-feels-like-from-within definition expresses the principal irreducible characteristic of the phenomenal aspect of consciousness: to experience something. “What it feels like to be me, to see red or to be angry” also emphasizes the subjective or first-person perspective of consciousness: it is a subject, an I, who is having the experiences and the experience is inevitably private.

What it feels like to have a particular experience is called the *quale* of that experience: the quale of red is what is common to such disparate conscious states as seeing a red sunset, the red flag of China, arterial blood, or a ruby gemstone. All four subjective states share “redness.” There are countless qualia (the plural of quale): the ways things look, sound and smell, the way it feels to have a pain, the way it feels to have thoughts and desires, and so on. To have an experience means to have qualia, and the quale of an experience is what specifies it and makes it different from other experiences.

A science of consciousness must explain the exact relationship between phenomenal, mental states and brain states. This is the heart of the classical mind-body problem: What is the nature of the relationship between the immaterial, conscious mind and its physical basis in the electro-chemical interactions in the body? This problem can be divided into several sub-problems.





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- (i) Why is there any experience at all? Or, put differently, why does a brain state feel like anything? In philosophy, this is referred to by some as the Hard Problem (note the capitalization), or as the explanatory gap between the material, objective world and the subjective, phenomenal world.¹ Many scholars have argued that the exact nature of this relationship will remain a central puzzle of human existence, without an adequate reductionistic, scientific explanation. However, as similar sentiments have been expressed in the past for the problem of seeking to understand life or to determine what material the stars are made out of, it is best to put this question aside for the moment and not be taken in by defeatist arguments.
- (ii) Why is the relationship among different experiences the way it is? For instance, red, yellow, green, cyan, blue, magenta are all colors that can be mapped onto the topology of a circle. Why? Furthermore, as a group, these color percepts share certain communalities that make them different from other percepts, such as seeing motion or smelling a rose.
- (iii) Why are feelings private? As expressed by poets and novelists, we cannot communicate an experience to somebody else except by way of example.
- (iv) How do feelings acquire meaning? Subjective states are not abstract states but have an immense amount of associated explicit and implicit feelings. Think of the unmistakable smell of dogs coming in from the rain or the crunchy texture of potato chips.
- (v) Why are only some behaviors associated with conscious states? Much brain activity and associated behavior occur without any conscious sensation.

3. The Neuronal Correlates of Consciousness

Progress in addressing the mind-body problem has come from focusing on empirically accessible questions rather than on eristic philosophical arguments. Key is the search for the neuronal correlates — and ultimately the



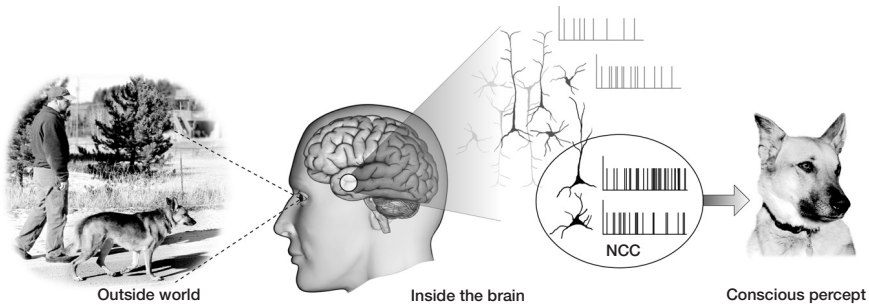


Fig. 1. The Neuronal Correlates of Consciousness (NCC) are the minimal set of neural events and structures — here synchronized action potentials in neocortical pyramidal neurons — sufficient for a specific conscious percept or a conscious (explicit) memory. From Ref. 4.

causes — of consciousness. As defined by Crick and Koch,^{3,68} the neuronal correlates of consciousness (NCC) are the *minimal neuronal mechanisms jointly sufficient for any one specific conscious percept* (Fig. 1).

This definition of NCC stresses the attribute *minimal* because the question of interest is which subcomponents of the brain are actually essential. For instance, it is likely that neural activity in the cerebellum does not underlie any conscious perception, and thus is not part of the NCC. That is, trains of spikes in Purkinje cells (or their absence) will not induce a sensory percept although they may ultimately affect some behaviors (such as eye movements).

On the other hand, the definition does not focus exclusively on the *necessary* conditions for consciousness because of the great redundancy and parallelism found in neurobiological networks. While activity in some population of neurons may underpin a percept in one case, a different population might mediate a related percept if the former population is lost or inactivated.

Every phenomenal, subjective state will have associated NCC: one for seeing a red patch, another one for seeing grandmother, yet a third one for hearing a siren, etc. Perturbing or inactivating the NCC for any one specific



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conscious experience will affect the percept or cause it to disappear. If the NCC could be induced artificially, for instance by cortical microstimulation in a prosthetic device or during neurosurgery, the subject would experience the associated percept.

What characterizes the NCC? What are the communalities between the NCC for seeing and for hearing? Will the NCC involve all pyramidal neurons in cortex at any given point in time? Or only a subset of long-range projection cells in frontal lobes that project to the sensory cortices in the back? Only layer 5 cortical cells? Neurons that fire in a rhythmic manner? Neurons that fire in a synchronous manner? These are some of the proposals that have been advanced over the years.⁵

It should be noted that discovering and characterizing the NCC in brains is not the same as a theory of consciousness (cf. Sec. 11). Only the latter can tell us why particular systems can experience anything, why they are conscious, and why other systems — such as the enteric nervous system or the immune system — are not. However, understanding the NCC is a necessary step toward such a theory.

4. The Neurobiology of Free Will

A further aspect of the mind-body problem is the question of free will, a vast topic. Answering this question goes to the heart of the way people think of themselves. The spectrum of views ranges from the traditional and deeply embedded belief that we are free, autonomous, and conscious actors to the view that we are biological machines driven by needs and desires beyond conscious access and without willful control.

Of great relevance are the classical findings by Libet and colleagues⁶ of brain events that precede the conscious initiation of a voluntary action. In this elegant experiment, subjects were sitting in front of an oscilloscope, tracking a spot of light moving every 2.56 sec around a circle. Every now and then, “spontaneously,” subjects had to carry out a specific voluntary action, here flexing their wrist. If this action is repeated sufficiently





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often while electrical activity around the vertex of the head is recorded, a *readiness potential* (*Bereitschaftspotential*) in the form of a sustained scalp negativity develops long before the muscle starts to move. Libet asked subjects to silently note the position of the spot of light when they first “felt the urge” to flex their wrist and to report this location afterwards. This temporal marker for the awareness of willing an action occurs on average 200 msec before initiation of muscular action (with a standard error of about 20 msec), in accordance with commonsense notions of the causal action of free will. However, the readiness potential can be detected at least 350 msec before awareness of the action. In other words, the subject’s brain signals the action at least half a second before the subject feels that he or she has initiated it.

This simple result has been replicated but, because of its counterintuitive implication that conscious will has no causal role, continues to be vigorously debated.⁷

Psychological work in both normal individuals as well as in patients reveals further dissociations between the conscious perception of a willed action and its actual execution: subjects believe that they perform actions that they did not do while, under different circumstances, subjects feel that they are not responsible for actions that are, demonstrably, their own.⁸

Yet whether volition is illusory or is free in some libertarian sense does not answer the question of how subjective states relate to brain states. The perception of free will, what psychologists call the *feeling of agency* or *authorship* (e.g., “I decided to lift my finger”), is certainly a subjective state with an associated quale no different in kind from the quale of a toothache or seeing marine blue. So even if free will is a complete chimera, the subjective feeling of willing an action must have some neuronal correlate.

Direct electrical brain stimulation during neurosurgery⁹ as well as fMRI experiments implicate medial pre-motor and anterior cingulate cortices in generating the subjective feeling of triggering an action.¹⁰ In other words, the neural correlate for the feeling of apparent causation involves activity in these regions.





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5. Quantum Mechanics and Consciousness

Neurobiologists and cognitive scientists implicitly assume that the relevant variables giving rise to consciousness are to be found at the neuronal level, among the synaptic release or the action potentials in population of neurons, rather than at the molecular, or even the sub-molecular, level — that the activity of neurons is responsible for all higher brain functions, including behavior, memory, emotion, and consciousness.

There is, however, also an alternative tradition that dates back to the early days of quantum mechanics¹¹ and to the supposedly critical role of the conscious observer in the measuring process. As is well known, it can be difficult to separate the process to be observed from the act of observing it. In more recent times, proposals for the critical role of quantum mechanics for consciousness have come from the physicist Roger Penrose¹² and others,¹³ as well as from the contemplative-meditative Buddhist school that also emphasizes the illusory nature of the object-subject distinction.¹⁴

The role of quantum mechanics for the photons received by the eye and for the molecules of life is undisputed. But although brains obey the laws of quantum mechanics, they do not seem to exploit any of its special features. Of particular interest here is *quantum entanglement*, the observation that the quantum states of multiple objects, such as two coupled electrons, may be highly correlated even though they are spatially separated, violating our intuition about locality (entanglement is the key feature of quantum mechanics exploited in quantum computers).

Molecular machines, such as the light-amplifying components of photoreceptors, pre- and post-synaptic receptors and the voltage- and ligand-gated channel proteins that span cellular membranes and underpin neuronal excitability, are so large that they can be treated as classical objects. Two key biophysical operations underlie information processing in the brain: chemical transmission across the synaptic cleft, and the generation of action potentials. These both involve thousands of ions and neurotransmitter molecules, coupled by diffusion or by the membrane potential that extends





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across tens of micrometers. Both processes will destroy any coherent quantum states. It follows that a neuron either spikes at a particular point in time or does not, but it is not in a superposition of spike and non-spike states. Thus, spiking neurons can only receive and send classical, rather than quantum, information.

The question of whether quantum mechanics governs the information processing in the brain also relates to the question of whether or not the brain as a complex dynamical system can be regarded as purely deterministic, i.e., *predictable* in a physical sense. A deterministic system of arbitrary complexity is in principle predictable if its initial state can be measured with arbitrary precision. The crucial question is whether or not quantum-mechanical uncertainty intrinsically limits this precision. The issue of determinism and predictability, in turn, relates to the problem of the free will (see Sec. 4).

At the moment, there is no evidence that any components of the nervous system — a 37°C wet and warm tissue strongly coupled to its environment — display quantum entanglement. At the cellular level, the interaction of neurons seems to be governed by classical physics.^{15,16}

Of course, it is very difficult to rigorously conclude that quantum mechanics is irrelevant to consciousness.[†] History is littered with pronouncements that certain things are not possible. The vertebrate brain is, after all, the product of an evolutionary selection process optimized over hundreds of millions of iterations.

[†]An interesting proposal is that by Bernroider¹⁷ that the two K⁺ ions in the selectivity filter of the closed voltage-dependent potassium channel — whose structure has been crystallized and characterized at the Angstrom level of resolution by MacKinnon and his colleagues¹⁸ — are in a superposition of two quantum states (S1/S3 and S2/S4). Even if true for such heavy ions — of molecular mass 39 u — it is not known how such an entanglement within a single channel could lead to entanglement across two or more potassium channels, let alone across neurons. Yet it is worth watching these and other developments and to keep an open mind.





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6. Consciousness in Other Species

Data about subjective states come not only from people who can talk about their subjective experiences but also from non-linguistic competent individuals — newborn babies or patients with complete paralysis of nearly all voluntary muscles (locked-in syndrome) — and, most importantly, from animals other than humans. There are three reasons to assume that many species, in particular those with complex behaviors such as mammals, share at least some aspects of consciousness with humans:

- (i) *Similar neuronal architectures*: Except for size, there are no large-scale, dramatic differences between the cerebral cortex and thalamus of mice, monkeys, humans and whales. In particular, the macaque monkey is a powerful model organism to study visual perception because it shares with the human visual system three distinct cone photopigments, binocular stereoscopic vision, a foveated retina and similar eye movements.
- (ii) *Similar behavior*: Almost all human behaviors have precursors in the animal literature. Take the case of pain. The behaviors seen in humans when they experience pain and distress — facial contortions, moaning, yelping or other forms of vocalization, motor activity such as writhing, avoidance behaviors at the prospect of a repetition of the painful stimulus — can be observed in all mammals and in many other species. Likewise for the physiological signals that attend pain: activation of the sympathetic autonomous nervous system resulting in change in blood pressure, dilated pupils, sweating, increased heart rate, release of stress hormones, and so on. The discovery of cortical pain responses in premature babies shows the fallacy of relying on language as the sole criterion for consciousness.¹⁹
- (iii) *Evolutionary continuity*: The first true mammals appeared at the end of the Triassic period, about 220 million years ago, with primates proliferating following the Cretaceous-Tertiary extinction event, about 60 million years ago, while humans and macaque monkeys did





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not diverge until 30 million years ago.²⁰ *Homo sapiens* is part of an evolutionary continuum with its implied structural and behavioral continuity, rather than an independently developed organism.

While certain aspects of consciousness, in particular those relating to the recursive notion of self and to abstract, culturally transmitted knowledge, are not widespread in non-human animals, there is little reason to doubt that other mammals share conscious feelings — sentience — with humans. To believe that humans are special, are singled out by the gift of consciousness above all other species, is a remnant of humanity's atavistic, deeply held belief that *homo sapiens* occupies a privileged place in the universe, a belief with no empirical basis.

The extent to which non-mammalian vertebrates — such as tuna, cichlid and other fish, crows, ravens, magpies, parrots and other birds, or even invertebrates, such as squids, or bees, with complex, non-stereo-typed behaviors including delayed-matching, non-matching-to-sample and other forms of learning²¹ — are conscious is difficult to answer at this point in time (but see Ref. 22). Without a sounder understanding of the neuronal architecture necessary to support consciousness, it is unclear where in the animal kingdom to draw the Rubicon that separates species with at least some conscious percepts from those that never experience anything and that are nothing but pure automata.²³

7. Level of Arousal and Content of Consciousness

There are two common, but quite distinct, usages of the term consciousness, one revolving around *arousal* and *states of consciousness* and another one around the *content of consciousness* and *conscious states*.

7.1. States of Consciousness and Conscious States

To be conscious of anything, the brain must be in a relatively high state of arousal (sometimes also referred to as *vigilance*). This is as true of





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wakefulness as it is of REM sleep that is vividly, consciously experienced in dreams, although usually not remembered. The level of brain arousal, measured by electrical or metabolic brain activity, fluctuates in a circadian manner and is influenced by lack of sleep, drugs and alcohol, physical exertion, etc. in a predictable manner. High arousal states are usually associated with some conscious state — a percept, thought or memory — that has a specific content. We see a face, hear music, remember an incident, plan an experiment, or fantasize about sex. Indeed, it is unlikely that one can be awake without being conscious of something. Referring to such conscious states is conceptually quite distinct from referring to states of consciousness that fluctuate with different levels of arousal. Arousal can be measured behaviorally by the signal amplitude that triggers some criterion reaction (for instance, the sound level necessary to evoke an eye movement or a head turn toward the sound source). Clinicians use scoring systems such as the Glasgow Coma Scale to assess the level of arousal in patients.

Different levels or states of consciousness are associated with different kinds of conscious experiences. The awake state in a normal functioning individual is quite different from the dreaming state (for instance, the latter has little or no self-reflection) or from the state of deep sleep. In all three cases, the basic physiology of the brain is changed, affecting the space of possible conscious experiences. Physiology is also different in *altered states of consciousness*, for instance after taking psychedelic drugs when events often have a stronger emotional connotation than in normal life. Yet another state of consciousness has been reported to occur during certain meditative practices, when conscious perception and insight are said to be enhanced compared to the normal waking state.

In some obvious but difficult to rigorously define manner, the *richness of conscious experience* increases as an individual transitions from deep sleep to drowsiness to full wakefulness. This richness of possible conscious experience could be quantified using notions from complexity theory that incorporate both the dimensionality as well as the granularity of conscious experience (e.g., the integrated-information-theoretical account





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of consciousness²⁴). Inactivating all of visual cortex in an otherwise normal individual would significantly reduce the dimensionality of conscious experience since no color, shape, motion, texture or depth could be perceived. As behavioral arousal increases, so does the range and complexity of behaviors that an individual is capable of. A singular exception to this progression is REM sleep where most motor activity is shut down in the *atonia* that is characteristic of this phase of sleep, and the person is difficult to wake up. Yet this low level of behavioral arousal goes, paradoxically, hand in hand with high metabolic and electrical brain activity and conscious, vivid states.

These observations suggest a two-dimensional graph (Fig. 2) in which the richness of conscious experience (its representational capacity) is plotted as a function of levels of behavioral arousal or responsiveness.

7.2. Global Disorders of Consciousness

Global disorders of consciousness can likewise be mapped onto this plane (Fig. 2). Clinicians talk about *impaired states of consciousness* as in “the *comatose state*,” “the *persistent vegetative state*” (PVS), and “the *minimally conscious state*” (MCS). Here, state refers to different levels of consciousness, from a total absence in coma, PVS and general anesthesia, to a fluctuating and limited form of conscious sensation in MCS, sleep walking or during a complex partial epileptic seizure.²⁶

The repertoire of distinct conscious states or experiences that are accessible to a patient in MCS is presumably minimal (mainly pain and discomfort, possibly sporadic sensory percepts), immeasurably smaller than the possible conscious states that can be experienced by a healthy brain. In the limit of brain death, the origin of this space has been reached with no experience at all (Fig. 2). A more desirable state is global anesthesia during which the patient should not experience anything — to avoid psychological trauma — but the level of arousal during the operation should be compatible with clinical exigencies. While anesthetics may, in principle, be useful for



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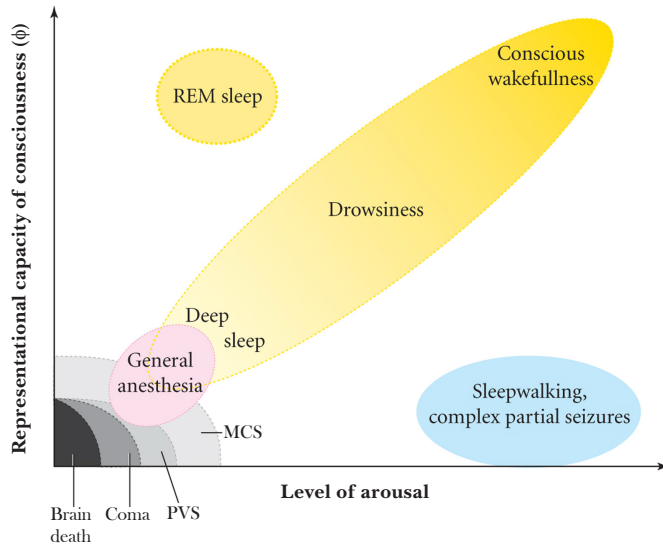


Fig. 2. Physiological and pathological brain states can be situated in a two-dimensional graph. Here increasing levels of behaviorally determined arousal are plotted on the x -axis and the “richness” or “representational capacity of consciousness”²⁴ is plotted on the y -axis. Increasing arousal can be measured by the threshold to obtain some specific behavior (for instance, spatial orientation to a sound). Healthy subjects cycle during a 24-hour period from deep sleep with low arousal and very little conscious experience to increasing levels of arousal and conscious sensation. In REM sleep, low levels of behavioral arousal go hand-in-hand with vivid consciousness. Conversely, various pathologies are associated with little or no conscious content. Modified from Ref. 25.

the study of consciousness, they have as yet failed to provide breakthrough insights about the Neural Correlates of Consciousness. This is mainly due to their diverse mechanisms of molecular action, targeting receptors throughout large parts of the brain. As our ability increases to differentiate subreceptor variation and target them with molecular tools by means of genetic *in vivo* studies,²⁷ this is likely to change.

Given the absence of any accepted theory for the minimal neuronal criteria necessary for consciousness, the distinction between a PVS patient — who shows regular sleep-wave transitions and who may be able to move their



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eyes or limbs or smile in a reflexive manner as in the case of Terri Schiavo in Florida — and an MCS patient — who can communicate (on occasion) in a meaningful manner (for instance, by differential eye movements) and who shows some signs of consciousness — is often difficult in a clinical setting. Functional brain imaging may prove immensely useful here.

Blood-oxygen-level-dependent functional magnetic resonance imaging (BOLD fMRI) recently demonstrated that a patient in a vegetative state following a severe traumatic brain injury showed the same pattern of brain activity as normals when asked to imagine playing tennis or visiting all the rooms in her house.²⁸ Differential brain imaging of patients with such global disturbances of consciousness (including akinetic mutism) reveal that dysfunction in a widespread cortical network including medial and lateral prefrontal and parietal associative areas is associated with a global loss of consciousness.²⁵ Impaired consciousness in epileptic seizures of the temporal lobe was likewise found to be accompanied by a decrease in cerebral blood flow in frontal and parietal association cortex and an increase in midline structures such as the mediodorsal thalamus.²⁹

7.3. Localized Brain Lesions affecting Consciousness

In contrast to diffuse cortical damage, relatively discrete bilateral injuries to midline (paramedian) subcortical structures can also cause a complete loss of consciousness. These structures are therefore part of the *enabling* factors that control the level of brain arousal (as determined by metabolic or electrical activity) and that are needed for any form of consciousness to occur. One such example is the heterogeneous collection of more than two dozen nuclei (on each side) in the upper brainstem (pons, midbrain and in the posterior hypothalamus) collectively referred to as the *reticular activating system* (RAS). These nuclei — three-dimensional collections of neurons with their own cytoarchitecture and neurochemical identity — release distinct neuromodulators such as acetylcholine, noradrenaline/norepinephrine, serotonin, histamine and orexin/hypocretin. Their axons project widely



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throughout the brain (Fig. 3). These neuromodulators control the excitability of thalamus and forebrain and mediate the alternation between wakefulness and sleep as well as the general level of both behavioral and brain arousal. Acute lesions of nuclei in the RAS can result in loss of consciousness and coma. However, eventually the excitability of thalamus and forebrain can recover and consciousness can return.³⁰ Another enabling factor for consciousness are the five or more intralaminar nuclei (ILN) of the thalamus. These receive input from many brainstem nuclei and project strongly to the basal ganglia and, in a more distributed manner, into layer I of much of neocortex. Comparatively small (1 cm^3 or less), bilateral lesions in the thalamic ILN completely knock out all awareness.³¹

In summary, a plethora of nuclei with distinct chemical signatures in the thalamus, midbrain and pons must function for a subject to be in a

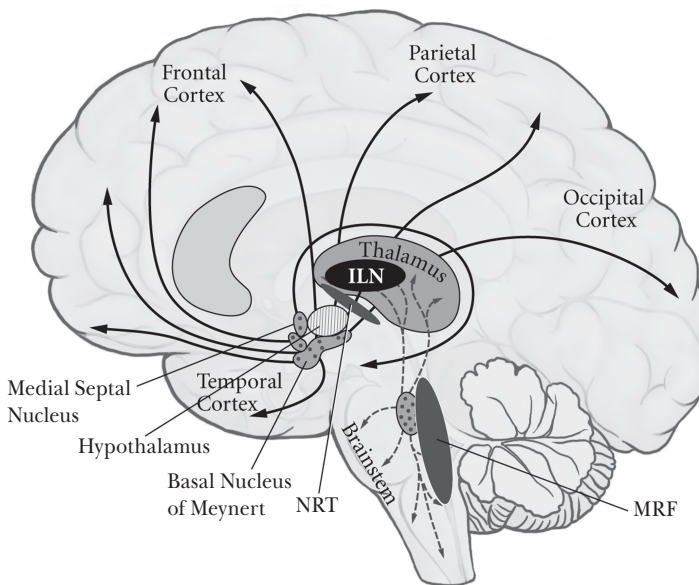


Fig. 3. Midline structures in the brainstem and thalamus necessary to regulate the level of brain arousal. Small, bilateral lesions in many of these nuclei cause a global loss of consciousness. From Ref. 4.



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sufficient state of brain arousal to experience anything at all. These nuclei belong to the enabling factors for consciousness. Conversely, it is likely that the specific content of any one conscious sensation is mediated by neurons in cortex and their associated satellite structures, including the amygdala, thalamus, claustrum and the basal ganglia.

7.4. Split-Brain Studies

The brain has a remarkable degree of bilateral symmetry. The mind, however, has but a single stream of consciousness, not two. Under ordinary conditions, the two hundred million fibers making up the corpus callosum, together with the anterior commissure and other minor bundles, integrate neural activity in the two halves of the forebrain such that only a single, integrated percept arises.

In certain cases of intractable epileptic seizures, part or all of the *corpus callosum* are surgically cut. Remarkably, after recovery, these patients usually act, speak, and feel no different than before. They do not complain of a loss of half their visual field or of other dramatic deficits. Upon closer inspection, however, a persistent and profound disconnection (split-brain) syndrome can be observed. If specific sensory information is provided to one or the other hemisphere, the information is not shared with its twin. A split-brain patient with typical (left hemispheric) language dominance is unable to name an image of an object presented in the left visual hemifield, but can pick this object from a group of objects using his left hand. This procedure involves conscious perception followed by a targeted motor response with the neural correlates necessarily being constrained to one hemisphere.

The primary conclusion from split-brain patients, work for which Roger Sperry was awarded the Nobel prize in 1981, is that both hemispheres are independently capable of conscious experience.^{32,33} Whatever the neuronal correlates of consciousness, these must exist independently in both cortical hemispheres.





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Another example of a complex impairment of conscious perception, not to be confused with the split-brain syndrome, is the neglect syndrome, properly called visuo-spatial hemi-neglect. It can be found after extensive damage typically to the right brain hemisphere with affection of the inferior parietal cortex. Patients with a hemi-neglect syndrome show an impaired awareness of their left visual hemifield despite the visual pathway being completely intact.

8. The Neuronal Basis of Conscious Perception

The possibility of precisely manipulating visual percepts in time and space has made vision a preferred modality in the quest for the NCC. Psychologists have perfected a number of techniques — masking, binocular rivalry, continuous flash suppression, motion-induced blindness, change blindness, inattention blindness — in which the seemingly simple and unambiguous relationship between a physical stimulus in the world and its associated percept in the privacy of the subject's mind is disrupted.³⁴ In particular, a stimulus can be perceptually suppressed for seconds or even minutes at a time: the image is projected into one of the observer's eyes but is invisible, not seen. In this manner the neural mechanisms that respond to the subjective percept rather than the physical stimulus can be isolated, permitting the footprints of visual consciousness to be tracked in the brain. In a *perceptual illusion*, the physical stimulus remains fixed while the percept fluctuates. The best known example is the *Necker cube* whose 12 lines can be perceived in one of two different ways in depth (Fig. 4).

A perceptual illusion that can be precisely controlled is *binocular rivalry*.³⁵ Here, a small image, e.g., a horizontal grating, is presented to the left eye, and another image, e.g., a vertical grating, is shown to the corresponding location in the right eye. In spite of the constant visual stimulus, observers consciously see the horizontal grating alternate every few seconds with the vertical one. The brain does not allow for the simultaneous perception of both images.





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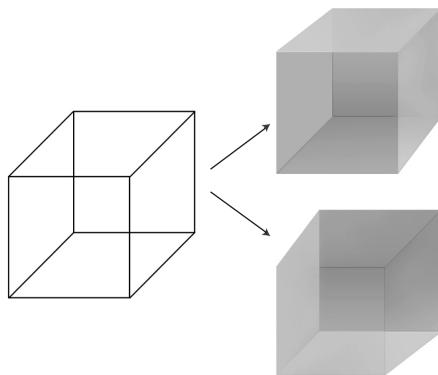


Fig. 4. The Necker Cube: The left line drawing can be perceived in one of two distinct depth configurations shown on the right. Without any other cue, the visual system flips back and forth between these two interpretations. From Ref. 4.

Macaque monkeys can be trained to report whether they see the left or the right image. The distribution of the switching times and the way in which changing the contrast in one eye affects these leaves little doubt that monkeys and humans experience the same basic phenomenon. In a series of elegant experiments, Logothetis and colleagues³⁶ recorded from a variety of visual cortical areas in the awake macaque monkey while the animal performed a binocular rivalry task. In primary visual cortex (V1), only a small fraction of cells weakly modulate their response as a function of the percept of the monkey. The majority of cells responded to one or the other retinal stimulus with little regard to what the animal perceived at the time. Conversely, in a high-level cortical area such as the inferior temporal (IT) cortex along the *ventral* (“*what?*”) *pathway*, almost all neurons responded only to the perceptually dominant stimulus (in other words, a “face” cell only fired when the animal indicated by its performance that it saw the face and not the pattern presented to the other eye; see Fig. 5), implying that the NCC involves activity in neurons in inferior temporal cortex.

Does this imply that the NCC is local to IT? At this point, no definitive answer can be given. However, given known anatomical connections, it is



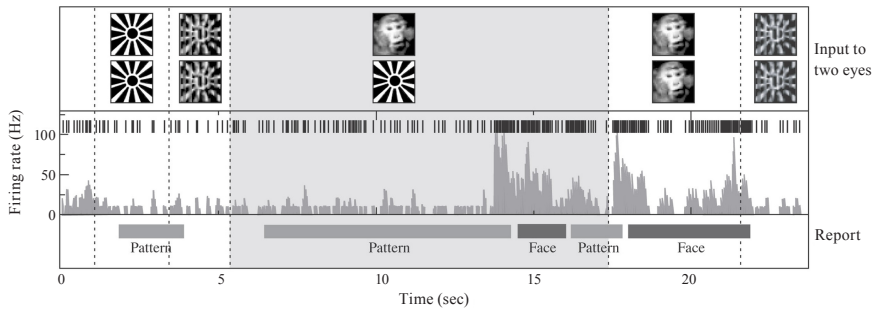


Fig. 5. A few seconds in the life of a typical IT cell while a monkey experiences binocular rivalry. The upper row indicates the visual input, with dotted vertical lines marking stimulus transitions. The second row shows the individual spikes, the third the smoothed firing rate, and the bottom row the monkey's behavior. The animal was taught to press a lever when it saw either one or the other image, but not both. The cell responded only weakly to either the sunburst pattern or to its optical superposition with the image of a monkey's face around 5 sec. During binocular rivalry (gray zone), the monkey's perception vacillated back and forth between seeing the face and seeing the bursting sun. Perception of the face was consistently accompanied (and preceded) by a strong increase in firing rate. From N. Logothetis (private communication) as modified by Ref. 4.

possible that specific reciprocal interactions between IT cells and neurons in parts of the prefrontal cortex are necessary for the NCC. This is compatible with the broadly accepted notion that the NCC must involve positive feedback to insure that neural activity is persistent and strong enough to exceed some threshold and be broadly distributed to multiple cognitive systems, including working memory, planning and language.

In a related perceptual phenomenon, *flash suppression*, the percept associated with an image projected into one eye is suppressed by flashing another image into the other eye (while the original image remains). Its methodological advantage over binocular rivalry is that the timing of the perceptual transition is determined by an external trigger rather than by an internal event. The majority of cells in IT cortex and in the superior temporal sulcus of monkeys trained to report their percept during flash suppression follow the animal's percept. That is, when the cell's preferred stimulus



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is perceived, the cell responds. If the picture is still present on the retina but is perceptually suppressed, the cell falls silent, even though legions of primary visual cortex neurons fire vigorously to this stimulus.^{37,38} Single neuron recordings in the medial temporal lobe of epilepsy patients during flash suppression likewise demonstrate abolishment of their responses when their preferred stimulus is present but perceptually masked.³⁹

In a powerful combination of binocular rivalry and flash suppression, a stationary image in one eye can be suppressed for minutes on end by continuously flashing different images into the other eye (continuous flash suppression).⁴⁰ This paradigm lends itself naturally to further investigate the relationship between neural activity — whether assayed at the single neuron or at the brain voxel level — and conscious perception.

A number of fMRI experiments have exploited binocular rivalry and related illusions to identify the hemodynamic activity underlying visual consciousness in humans. They demonstrate quite conclusively that BOLD activity in the upper stages of the ventral pathway (e.g., the fusiform face area and the parahippocampal place area) as well as in early regions, including V1 and the lateral geniculate nucleus (LGN), follow the percept and not simply the retinal stimulus.⁴¹ Furthermore, a number of elegant fMRI experiments^{42,43} support the hypothesis that V1 is necessary, but not sufficient for visual consciousness for normal seeing.⁴⁴ It remains an open question as to whether V1 is necessary to enjoy the vivid visual dreams that are consciously experienced and that occur most frequently during REM sleep when the eyes are closed.⁴⁵

9. Other Perceptual Puzzles of Contemporary Interest

The attributes of even simple percepts seem to vary along a continuum. For instance, a patch of color has a brightness and a hue that are variable, just as a simple tone has an associated loudness and pitch. However, is it possible that each particular, consciously experienced, percept is all-or-none? Might





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a pure tone of a particular pitch and loudness be experienced as an atom of perception, either heard or not, rather than gradually emerging from the noisy background? The perception of the world around us would then be a superposition of many elementary, binary percepts.⁴⁶

Is perception continuous, like a river, or does it consist of series of discontinuous batches, rather like the discrete frames in a movie^{47,48}? In cinematographic vision,⁴⁹ a rare form of visual migraine, the subject sees the movement of objects as fractured in time, as a succession of different configurations and positions, without any movement in-between. The hypothesis that visual perception is quantized in discrete batches of variable duration, most often related to EEG rhythms in various frequency ranges (from theta to beta), is an old one. This idea is being revisited in light of the discrepancies of timing of perceptual events within and across different sensory modalities. For instance, even though a change in the color of an object occurs simultaneously with a change in its direction of motion, it may not be perceived that way.^{50–52}

What is the relationship between endogenous, top-down attention and consciousness? Although these are frequently coextensive — subjects are usually conscious of what they attend to — there is a considerable tradition in psychology that argues that these are distinct neurobiological processes.⁵³ This question is receiving renewed “attention” due to the development of ever more refined and powerful visual masking techniques³⁴ that independently manipulate attention and consciousness. Indeed, it has been shown that attention can be allocated to a perceptually invisible stimulus⁵⁴ and that subjects can be conscious of a stimulus without attending to it. When exploring the neural basis of these processes, it is therefore critical to not confound attention with consciousness and *vice versa*.

10. Forward Versus Feedback Projections

Many actions in response to sensory inputs are rapid, transient, stereotyped, and unconscious.⁵⁵ They could be thought of as cortical reflexes and are





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characterized by rapid and somewhat stereotyped responses that can take the form of rather complex automated behavior as seen, e.g., in complex partial epileptic seizures. These automated responses, sometimes called *zombie behaviors*,⁵⁶ could be contrasted by a slower, all-purpose conscious mode that deals more slowly with broader, less stereotyped aspects of the sensory inputs (or a reflection of these, as in imagery) and takes time to decide on appropriate thoughts and responses. Without such a consciousness mode, a vast number of different zombie modes would be required to react to unusual events.

A feature that distinguishes humans from most animals is that we are not born with an extensive repertoire of behavioral programs that would enable us to survive on our own (“physiological prematurity”). To compensate for this, we have an unmatched ability to learn, i.e., to consciously acquire such programs by imitation or exploration. Once consciously acquired and sufficiently exercised, these programs can become automated to the extent that their execution happens beyond the realms of our awareness. Take as an example the incredible fine motor skills exerted in playing a Beethoven piano sonata or the sensorimotor coordination required to ride a motorcycle along a curvy mountain road. Such complex behaviors are possible only because a sufficient number of the subprograms involved can be executed with minimal or even suspended conscious control.

In fact, the conscious system may actually interfere somewhat with these automated programs⁵⁷: focusing consciousness onto the smooth execution of a complex, rapid and highly trained sensory-motor task — dribbling a soccer ball, to give one example — can interfere with its smooth execution, something well known to athletes and their trainers.

From an evolutionary standpoint it makes sense to have both automated behavioral programs that can be executed rapidly in a stereotyped and automated manner, and a slightly slower system that allows time for thinking and planning more complex behavior. This latter aspect, planning, may be one of the principal functions of consciousness.





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It seems possible that visual zombie modes in the cortex mainly use the *dorsal* (“where?”) pathway in the parietal region.⁵⁵ However, parietal activity can affect consciousness by producing attentional effects on the ventral stream, at least under some circumstances. The basis of this inference are clinical case studies and fMRI experiments in normal subjects.⁵⁸ The conscious mode for vision depends largely on the early visual areas (beyond V1) and especially on the ventral stream.

Seemingly complex visual processing (such as detecting animals in natural, cluttered scenes) can be accomplished by the human cortex within 130–150 msec,^{48,59} way too fast for eye movements and conscious perception to occur. Furthermore, reflexes such as the oculovestibular reflex take place at even more rapid time scales. It is quite plausible that such behaviors are mediated by a purely feed-forward moving wave of spiking activity that passes from the retina through V1, into V4, IT and prefrontal cortex, until it affects motor-neurons in the spinal cord that control the finger press (as in a typical laboratory experiment). The hypothesis that the basic processing of information is feed-forward is supported most directly by the short times (approx. 100 msec) required for a selective response to appear in IT cells.

Conversely, conscious perception is believed to require more sustained, reverberatory neural activity, most likely via global feedback from frontal regions of neocortex back to sensory cortical areas.⁴⁴ These feedback loops would explain why in backward masking a second stimulus, flashed 80–100 msec after onset of a first image, can still interfere (mask) with the percept of the first image. The reverberatory activity builds up over time until it exceeds a critical threshold. At this point, the sustained neural activity rapidly propagates to parietal, prefrontal and anterior cingulate cortical regions, thalamus, claustrum and related structures that support short-term memory, multi-modality integration, planning, speech and other processes intimately related to consciousness. Competition prevents more than one or a very small number of percepts to be simultaneously and actively represented. This is the core hypothesis of the *global workspace*





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model of consciousness.^{60,61} Sending visual information to more frontal structures would allow the associated visual events to be decoded and placed into context (for instance, by accessing various memory banks) and to have this interpretation feed back to the sensory representation in visual cortex.⁶²

In brief, while rapid but transient neural activity in the thalamo-cortical system can mediate complex behavior without conscious sensation, it is surmised that consciousness requires sustained but well-organized neural activity dependent on long-range cortico-cortical feedback.

11. An Information-Theoretical Theory of Consciousness

At present, it is not known to what extent animals whose nervous systems have an architecture considerably different from the mammalian neocortex are conscious (see Sec. 6). Furthermore, whether artificial systems, such as computers, robots or the World Wide Web as a whole, which behave with considerable intelligence, are or can become conscious (as widely assumed in science fiction, e.g., the paranoid computer *HAL* in the film *2001*), remains completely speculative. What is needed is a theory of consciousness, which explains in quantitative terms what type of systems, with what architecture, can possess conscious states.

While discovering and characterizing the NCC is a necessary step in understanding consciousness, such an opportunistic, data-driven approach cannot explain why certain structures and processes have a privileged relationship with subjective experience. For example, why is it that neurons in corticothalamic circuits are essential for conscious experience, whereas cerebellar neurons, despite their huge numbers, are most likely not? And what is wrong with cortical zombie systems that makes them unsuitable for yielding subjective experience? Or why is it that consciousness wanes during slow-wave sleep early in the night, despite levels of neural firing in the thalamocortical system that are comparable to the levels of firing in wakefulness?





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Information theory may be such a theoretical approach that establishes at the fundamental level what consciousness is, how it can be measured, and what requisites a physical system must satisfy in order to generate it.^{1,63}

The most promising candidate for such a theoretical framework is the *information integration theory of consciousness*.²⁴ It posits that the most important property of consciousness is that it is extraordinarily *informative*. Any one particular conscious state rules out a huge number of alternative experiences. Classically, the reduction of uncertainty among a number of alternatives constitutes information. For example, when a subject consciously experiences reading this particular phrase, a huge number of other possible experiences are ruled out (consider all possible written phrases that could have been written in this space, in all possible fonts, ink colors, and sizes, think of the same phrases spoken aloud, or read and spoken, and so on). Thus, every experience represents one particular conscious state out of a huge repertoire of possible conscious states.

Furthermore, information associated with the occurrence of a conscious state is *integrated* information. An experience of a particular conscious state is an integrated whole. It cannot be subdivided into components that are experienced independently.⁶³ For example, the conscious experience of this particular phrase cannot be experienced as subdivided into, say, the conscious experience of how the words look independently of the conscious experience of how they sound in the reader's mind. Similarly, visual shapes cannot be experienced independently of their color, nor can the left half of the visual field of view be experienced independently of the right half.

Based on these and other considerations, the theory claims that *a physical system can generate consciousness to the extent that it can integrate information*. This idea requires that the system has a large repertoire of available states (information) yet cannot be decomposed into a collection of causally independent subsystems (integration).

Importantly, the theory introduces a measure of a system's capacity to integrate information. This measure, called ϕ , is obtained by determining the minimum repertoire of different states that can be produced in one part





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of the system by perturbations of its other parts.²⁴ ϕ can loosely be thought of as the representational capacity of the system (as in Fig. 2). Although ϕ is not easy to calculate exactly for realistic systems, it can be estimated. Thus, by using simple computer simulations, it is possible to show that ϕ is high for neural architectures that conjoin functional specialization with functional integration, like the mammalian thalamocortical system. Conversely, ϕ is low for systems that are made up of small, quasi-independent modules, like the cerebellum, or for networks of randomly or uniformly connected units.²⁴

The notion that consciousness has to do with the brain's ability to integrate information has been tested directly by transcranial magnetic stimulation (TMS). In TMS a coil is placed above the skull and a brief and intense magnetic field generates a weak electrical current in the underlying grey matter in a noninvasive manner. Massimini *et al.*⁶⁴ compared multichannel EEG of awake and conscious subjects in response to TMS pulses to the EEG when the same subjects were deeply asleep early in the night — a time during which consciousness is much reduced. During quiet wakefulness, an initial response at the stimulation site was followed by a sequence of waves that moved to connected cortical areas several centimeters away. During slow wave sleep, by contrast, the initial response was stronger but was rapidly extinguished and did not propagate beyond the stimulation site. Thus, the fading of consciousness during certain stages of sleep may be related, as predicted by the theory, to the breakdown of information integration among specialized thalamocortical modules.

12. Conclusion

Ever since the Greeks first formulated the mind-body problem more than two millennia ago, it has been the domain of armchair speculations and esoteric debates with no apparent resolution. Yet many aspects of this ancient set of questions now fall squarely within the domain of science.

Progress in the study of the NCC on the one hand, and of the neural correlates of non-conscious behaviors on the other, will hopefully lead to a





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better understanding of what distinguishes neural structures or processes that are associated with consciousness from those that are not.

The growing ability of neuroscientists to manipulate in a reversible, transient, deliberate and delicate manner identified populations of neurons using methods from molecular biology⁶⁵ in combination with optical tools⁶⁶ opens up the possibility of moving from correlation — observing that a particular conscious state is associated with some neural or hemodynamic activity — to causation. Exploiting these increasingly powerful tools depends on the simultaneous development of appropriate behavioral assays and model organisms amenable to large-scale genomic analysis and manipulation.⁶⁷

It is the combination of such fine-grained neuronal analysis in animals with ever more sensitive psychophysical and brain imaging techniques in humans, complemented by the development of a robust theoretical predictive framework, that will hopefully lead to a rational understanding of consciousness, one of the central mysteries of life.

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