The Conscious Brain
Some Views, Concepts, and Remarks from a Neurobiological Perspective

Dariusz Adamek, Józef Bremer

ABSTRACT The goal of this article is to review some aspects of brain anatomy and neurophysiology that are important for consciousness, and which hopefully may be of benefit to philosophers investigating the conscious mind. Taking as an initial point of reference the distinction between "the hard problem" and "the weak problems" of consciousness, we shall concentrate on questions pertaining to the second of these. A putative "consciousness system" in the brain will be presented, paying special attention to diffuse projection systems. The "center of gravity" will be brain connectivity, since consciousness must, critically, be dependent on coherent activity and timing. "Detectors" of synchronicity and coincidence, like NMDA receptors, also necessarily play a role here. To be conscious, we do not need an entire brain. While even large hemispherectomies need not unequivocally affect consciousness, far smaller brain-stem lesions may be devastating in this regard. Even so, the recent discovery by Matthew F. Glasser et al. of 180 separate areas in the human brain cortex is intriguing from a teleological perspective, as it is quite unthinkable that any of them could be "redundant.

KEYWORDS brain anatomy; cognition; diffuse projecting systems (of brain); connectivity; consciousness; neural event; NMDA; synchronicity

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INTRODUCTION

Consciousness could be defined as:

(a) the state of awareness of oneself (self-consciousness);

Questions connected with this are known as "the hard problem" of consciousness,[1] and are mostly analyzed in terms of either the problem of explaining how and why we have qualia or phenomenal experiences (sensations, tastes, colors . . .), or the question of subjectivity—roughly, "what it is like to be me." We shall call this the phenomenal aspect of consciousness ("phenomenal consciousness").

(b) the condition of our being able to perceive stimuli coming from our environment and respond to them appropriately.

Such aspects of consciousness are called "access consciousness," and are treated as belonging to "the easy problems" of consciousness. This term covers problems connected with explaining our ability to distinguish things, assimilate information, report mental states, focus attention, etc. Chalmers calls such problems "easy," because all that is necessary for their solution is to specify a mechanism (usually a neuronal mechanism) that can perform the function.

In other words, proposed solutions to this second class of problems, irrespective of how complexly or sparsely understood they may be, can be perfectly consistent with modern reductionist-materialistic conceptions of natural phenomena. The problem of qualia (or subjective, qualitative experiences), on the other hand, is at odds with this reductionist-materialist conception and, according to Chalmers, the hardness of this problem will persist even when the performance of all significant functions has been explained. Taken together, (a) and (b) imply that the consciousness system fulfills two crucial functions: (i) delivering the content of experience (i.e., the phenomenal contents of consciousness), and (ii) preservation of a state of wakefulness (perceiving and responding to stimuli).[2]

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[1] The philosopher David Chalmers introduced the phrase "hard problem of consciousness," opposing this to what he calls "easy problems." David J. Chalmers, "Facing Up to the Problem of Consciousness," *Journal of Consciousness Studies* 2, no. 3 (1995), doi:10.1093/acprof:oso/9780195311105.003.0001; cf. Stephen Grossberg, "Towards Solving the Hard Problem of Consciousness: The Varieties of Brain Resonances and the Conscious Experiences That They Support," *Neural Networks* 87 (2017), doi:10.1016/j.neunet.2016.11.003; Józef Bremer, *Jak to jest być świadomym. Analityczne teorie umysłu a problem neuronalnych podstaw świadomości* (Warsaw: IFiS PAN, 2005).

Every time we—as philosophers or neuropathologists—approach the living or dead brain, we cannot help but entertain feelings and reflections concerning the "existential weight" of what we are about to become involved with. Nevertheless, the medical goal of the neuropathologist engaged in investigating brain tissue during an examination is highly mundane and strictly pragmatic. ("Is there or is there not a tumor?" "Should surgery be carried out or not?") Yet as philosophers we ask "What about consciousness?" and in our case, also, "What about the neuronal mechanisms for conscious attention, for gathering information?" We know that consciousness can be generated in relatively small quantities of brain tissue, but its computational power and effectiveness in the world require a massive supporting system of perceptual organs, executive processes to direct processing, and effectors to create behavior that alters the environment.[3] So, what about consciousness?

On the one hand—without going into details—the processes or activity of nerve cells or tissue, inasmuch as these can be said to "overflow" into actual consciousness and thought, remain essentially unknown. On the other, neurophysiology has yielded some understanding of the brain regions, the nerve pathways, and the neurotransmitters which produce the various states of both of the above-mentioned aspects of "consciousness." One may justifiably assume that "consciousness" does not emerge from a single brain structure, but rather derives from an interaction involving many parts of the brain. Some neurobiologists claim that there exists a "consciousness system" in the brain that roughly consists of medial and lateral frontoparietal association cortices and arousal circuits in the upper part of the brainstem and diencephalon.

In this article, we shall explore the notion of a neuronal mechanism involved in the consciousness system. We use the term "consciousness system" or "consciousness" to describe those states in which we have thoughts and awareness, states that might be described as "alert" or "enhanced," as well as "drowsiness" (when we are awake but distracted) and, finally, the particular sort of consciousness associated with slow-wave and REM sleep. It is crucial to realize that detailed discussion lies beyond the

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2. That function could be partially estimated by using one of the most common scoring system: the Glasgow Coma Scale (GCS)—a neurological scale which intends to give a credible and objective manner of recording the conscious state of a person for primary as well as following assessment.

3. William Hirstein, "Conscious States: Where Are They in the Brain and What Are Their Necessary Ingredients?," *Mens Sana Monographs* 11, no. 1 (2013), doi:10.4103/0973-1229.109343.

scope of this article, and that only those elements essentially relevant to the medical and philosophical point of view will be touched on here.

The "center of gravity" of this paper will be brain connectivity, since if we assume that consciousness is an emergent property of the brain / mind, and (rather obviously) not a "function" of some particular "tissue," "center," or "system" in the brain, then consciousness must be critically dependent on coherent activity on the part of the brain as (more or less) a whole. Even just intuitively, one must agree that any coherent activity *must* in turn be dependent on proper timing and, lastly, timing in the brain obviously depends on the functional integrity and properties of the network of nerve fibers: i.e. connectivity.

1. ESSENTIAL TENETS

Let us begin by formulating the basic tenets—and with this the central assumptions, questions and topics—of the present article:

(1) COHERENCE. Consciousness is supposed to be critically dependent on the coherent activity of multiple, more or less anatomically allocated "centers" of the brain. This "coherence" in respect of activity means that the activity in question must be coordinated in time within very strict limits (as if "orchestrated").

(2) CONNECTIVITY. Consciousness is unimaginable without proper anatomical and functional connections, since connectivity is crucial for the integrative character of the workings of the brain. We must assume the existence of an anatomical and functional network-like system of intra-brain communication that is extremely fast, enabling the coordination of numerous "events" of activity across different centers of the brain with extreme time-precision.

(3) DETECTION OF COINCIDENCE. Regarding the terms "coherence" and "orchestrated" mentioned in COHERENCE, the key functional-structural elements of brain tissue are consequently those that allow the detection of coincidence.

(4) "ON-OFF MECHANISM." The fact that the transition from unconscious to conscious is quite abrupt (we need only recall everyday experiences of waking from nocturnal sleep), while the "woken-up" brain / mind behaves in precisely the same way as before losing consciousness, suggests that there must be a dedicated system that can "switch on and off" the rest of the brain. Hence, let us consider and present a putative "consciousness system" of the brain.

(5) REDUNDANCY. Apparent "redundancy" (one can remove quite a lot of brain tissue without this affecting consciousness or disturbing a patient's feeling of self-identity) speaks in favor of the hypothesis that it is possible for there to be more than a single mind in the same individual.

2. FIRST TENET: COHERENCE

In expounding this tenet, we shall first consider the term "center," and then that of "coherence." Our conception of and knowledge about brain centers dates back over a century and a half, to the discoveries in the mid-nineteenth century of Broca and Wernicke, who encountered particular focal lesions of the brain associated with specific neurological deficits (in their case, aphasia). These lesions are located in the brain cortex (containing bodies of neurons). However, although the brain cortex is primarily affected, since this is especially sensitive to ischemia, to at least some extent adjacent white matter is also affected. We know that there are many "places," or anatomical structures, that we call the "eloquent" ones. Damage to or removal of those structures will result in clearly noticeable clinical manifestations. Damage to some particular regions may result in a loss of sensory processing or linguistic ability, minor paralysis, or paralysis. The most prominent areas of the eloquent cortex are in the left temporal and frontal lobes, and are correlated with abilities of the kind generally regarded as essential in the context of philosophical and/or cognitivistically oriented research focused on the human person: e.g. speech, language and, more broadly, the general ability to perform symbolic communication. Examples of other eloquent regions are the bilateral occipital lobes for vision, the bilateral parietal lobes for sensation, and the bilateral motor cortex for movement. The eloquent brain regions pose a complex challenge for neurosurgeons—one that requires a multidisciplinary team-based approach to making decisions as regards the extent of any operation to be performed. The benefits of resecting as much tumor as possible to increase survival must be carefully balanced against the risk of compromising neurological function and decreasing the quality of the patient's life.[4]

Nevertheless, from a quantitative perspective the areas in the brain that seem apparently to be "silent" prevail. In other words, areas that one might

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[4] John Park, "Tumor Resection from Eloquent Brain Areas," *NEUROtransmitter* magazine (Santa Barbara Neuroscience Institute), Spring 2015, 6–7, https://www.cottagehealth.org/app/files/public/1099/neurotransmitter_park02_spring15.pdf.

easily regard as being either auxiliary or even redundant prevail. But are they? The concept of "center" is inseparably linked to that of locality. That the functioning of the brain must be "local" finds support in the very widely noted phenomenon of coupling between the focal level of activity in the brain and the value of local blood perfusion and glucose uptake. The most popular method of functional imaging of the brain—the so called BOLD method—shows innumerable regions of the brain appearing and disappearing as we observe increased neuronal activity in them (via increased blood perfusion coupled to neuronal activity). Many of these regions do not have specific names, but their activity patterns are starting to be more and more closely linked to particular mental tasks.[5] There is wide agreement that both consciousness and cognitive capacities benefit from the presence of a large pool of accessible centers (and states connected with these), as well as the ability to switch between them. This is supported by findings to the effect that the dynamic repertoire of the brain is drastically decreased during sleep and under anesthesia.[6]

Now let us consider the remaining key words that were used to state the tenet in question: namely, "coherence" (which, in fact, is inseparable from the concept of "time") and other linked terms. Indeed, neither "coherence" nor "coordination" will be discernible without some sort of temporal perspective.

We may try to imagine, and furnish an example of, a "unitary conscious event," understood in terms of neurobiology / neurophysiology. Allow us, then, to assume that the "content" of such a unitary event will be triggered by an external visual stimulus (a visual "picture"). The brain must be in a wakeful state, and be able to switch from sustained to directed attention. A "picture" should be perceived, an object has to be discerned, and all its aspects (color, shape, etc.) and meaning (recognition of the category of the object, its name or, at least, some simpler associated information retrieved from memory, emotional salience, etc.) acknowledged. Many structures of the brain, and not just visual ones, must be involved in all the particular tasks necessary for this event to occur. They will be ad-

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[5] However, one should not forget that, unfortunately, the BOLD method, as an indirect way of carrying out functional brain imaging, suffers from an inherent problem in the form of a delay between the real excitation of neurons and the increasing of local blood perfusion.

[6] Gorka Zamora-López, Yuhan Chen, Gustavo Deco, Morten L. Kringelbach, and Changsong Zhou, "Functional Complexity Emerging from Anatomical Constraints in the Brain: The Significance of Network Modularity and Rich-clubs," *Scientific Reports* 6 (2016), article 38424, doi:10.1038/srep38424.

umbrated later (as parts of the consciousness system). All these "elements" of the cognitive event should occur at the appropriate time and be effectively "bound" (where this refers to the so called problem of "binding") and memorized. The search for the neuronal substrate of consciousness or awareness therefore converges with the search for the cognitive mechanisms through which brains analyze their environment.[7] Even during a short interval of time, the information (in practice the neuronal "signaling") conveyed between the many centers (i.e., parts of the consciousness system) probably has to pass across many times, and any delay in this process may result in defective or disturbed consciousness. Hence, it is rather obvious that the key to all this is the brain's connectivity.

3. Second Tenet: Connectivity

Consciousness is inconceivable without proper anatomical and functional connections, as connectivity is crucial to the integrative character of the workings of the brain. Here we encounter the role of white matter: i.e. the compartment of the central nervous system that contains nothing but neuronal processes (myelinated axons, to whom "white" matter owes its name), supporting glial cells and blood vessels, but not the neurons' cell bodies or more precisely their perikaryal parts. Hence, white matter is where the signals (information) are conveyed, but (most probably) not integrated or "processed."[8]

Some investigations have found that a loss of myelinated nerve fibers, and a slowing down of the rate of conduction along them, leads to cognitive impairment of the kind that occurs with increasing age. Some loss of nerve fibers in white matter may, in fact, be not necessarily correlated with a loss of neurons in the cortex, and the loss of fibers may be more marked than the loss of neurons. Alan Peters, who has investigated the state of myelinated fibers in relation to the age of monkeys, stresses that timing in the neuronal circuits would be affected, and this would contribute to the sort of cognitive impairment that occurs with increasing age. The frequency of occurrence of myelin sheath alterations in some

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[7] Richard A. Mould, "A Solution to the Binding Problem," *Journal of Behavioral and Brain Science* 6, no. 3 (2016), doi:10.4236/jbbs.2016.63013.

[8] Even so, it is still hypothetically possible that signals conducted along nerve fibers positioned closely together might mutually influence each other, as in the phenomenon known as "ephaptic coupling." Nevertheless, showing whether this plays any role in the brain would require substantial evidence, of a kind currently lacking.

prominent association fibers,[9] such as the cingulum bundle, fornix, and the splenium of the corpus callosum, have been found to correlate with cognitive decline in monkeys (see the review by Peters and Kemper[10]). No sort of coordination in respect of the activity of separate brain centers can be imagined in the absence of systems that are able to synchronically affect at least many parts of it, if not the whole brain.

The systems that may serve such a goal are called "diffuse projection systems." These systems have some particular features. They are formed of neuronal fibers located in small, highly compacted, anatomic places (nuclei) and use the same specific neurotransmitters (in each particular system): acetylcholine, dopamine, noradrenaline, etc. (in some of them the dominant neurotransmitter is uncertain). As a result, there exist separate cholinergic, dopaminergic, noradrenergic, etc. projection systems that put out such fibers not only to almost the entire cortex, but also to extracortical regions of the brain (e.g., the cerebellum, brainstem). Almost all these systems take part in the regulation of alertness, and the sleep-wake cycle, while some are also implicated in emotional states, movement control, memory and other cognitive functions and aspects of consciousness. In particular, it is rather impossible to imagine an effective transition from being alert to being asleep, or vice-versa, without a system (or systems) that can affect the activity of more or less the whole of the brain, and there do in fact exist diffuse projection systems of precisely the kind that would be responsible for this job. The diffuse projections systems are summarized in Table 1.

With the probably exception of the dopaminergic projection system, all of the others mentioned in Table 1 are involved in alertness, which can be viewed as a basic condition for promoting consciousness, or a basic "level" of consciousness (see section "Fourth Tenet: 'ON-OFF MECHANISM' " on the consciousness system in the brain, page 18). In particular, it is worth

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[9] The connective structures of the brain are anatomically divided into association fibers (which connect different regions of the cortex within the same hemisphere), projecting fibers (connecting different but specific structures of the central nervous system, roughly in rostro-caudal orientation), and commissural fibers (connecting the two hemispheres). Moreover, in contradistinction to the projecting fibers defined above, which may be characterized as "specific" in that they bind particular regions or nuclei within the central nervous system, there also exist so called "diffuse projecting systems" (explained below).

[10] Alan Peters and Thomas Kemper, "A Review of the Structural Alterations in the Cerebral Hemispheres of the Aging Rhesus Monkey," *Neurobiology of Aging* 33, no. 10 (2012), doi:10.1016/j.neurobiolaging.2011.11.015; Alan Peters, "The Effects of Normal Aging on Myelinated Nerve Fibers in Monkey Central Nervous System," *Frontiers in Neuroanatomy* 3 (July 2009), article 11, doi:10.3389/neuro.05.011.2009.

Table 1. Diffuse projection systems of the brain

Neurochemical type of diffuse projecting system (and type of chemical neurotransmiter)	Location of basic groups of neurons (nuclei)
1. cholinergic (ester)	nucleus basalis of Meynert, medial septal nucleus, nucleus of diagonal band, pedunculopontine nucleus, laterodorsal tegmental nucleus
2. dopaminergic (monoamine)	ventral tegmental area, substantia nigra pars compacta
3. noradrenergic (monoamine)	nucleus locus coeruleus, lateral tegmental area
4. serotoninergic (monoamine)	raphe nuclei of midbrain, pons, medulla
5. histaminergic (monoamine)	tuberomammillary nucleus
6. orexinergic (peptide)	neurons around tuberomammillary nucleus
7. reticular formation (probably aminoacid—glutamate?)	reticular formation of brainstem, esp. pontomesencephalic reticular formation
8. thalamic intralaminar and midline nuclei (probably aminoacid—glutamate?)	thalamus

noting that pontomesencephalic reticular formation and thalamic intralaminar and midline nuclei play a special role in alertness.

With a view to adducing instances of the diffuse projection systems of the brain, we may describe the reticular formation as a complex collectivity of neurons with their cell bodies and processes. They build up clusters in the tegmentum of the brainstem, the basal forebrain, and the thalamus. The reticular formation has enormous afferent and efferent connections, ranging from the cerebral cortex, thalamus and hypothalamus to the spinal cord. Usually, such tremendous pathways belonging to the reticular formation can be described as falling into two parts, the rostral part and the caudal part. The rostral part of the reticular formation begins roughly at the level of the upper pons and midbrain, and contains neurochemically classified groups of neurons that project to the cerebral cortex either directly or by relay in the thalamus. This is the reticular ascending pathway and it is important in the consciousness system. The caudal part has projections to the spinal cord and is involved in the control of important motor function, respiration and the regulation of blood pressure. This is the descending pathway. Although it is divided as such, we should keep in mind that the ascending pathway does run up from the medulla as well.

In order to further comprehend the consciousness system, the ascending pathway can be categorized into different groups or nuclei by virtue of its neurochemical nature: i.e. cholinergic and monoaminergic systems. Interestingly, both these systems project extensively to the cerebral cortex via the medial forebrain bundle (belonging to the aforementioned "specific" projecting fibers). This is a large tract that extends from the midbrain tegmentum through the lateral hypothalamus and into the septum and preoptic area. Some of the fibers from the medial forebrain bundle enter the cingulate gyrus.

In general, it is supposed that the diffuse projection systems of the brain can be regarded as "pacemakers" and regulators of both brain activity generally and particular cognitive tasks. The effectiveness of the pacemaking network will inevitably require the fastest possible transduction of signals through nerve fibers. Regarding my own observations (D.A.), inspecting histological slides of brains stained for myelin, one encounters here and there single fibers that are strikingly thicker than all the rest. These, one presumes, will constitute only a minute fraction of a percent of all of the fibers (my bet would be a maximum of about one-in-a-thousand, but quite possibly less). Moreover, according to these observations such very thick fibers frequently do not run alongside the adjacent bundles of fibers, but cross them at some angle or other.[11] In our view, these (rare) thickest fibers are best fitted to the job of ensuring time coordination and coherence with respect to the activity of different centers, since according to the basic electrophysiological rules of nerve conduction, the thicker the fiber, the faster the rate of transduction. These fibers seem to occur in the whole brain, though my (educated?) guess is that they are more frequently to be found in white matter belonging to the cerebral hemispheres (D.A). One can hypothesize that the thickest nerve fibers, being more sparsely dispersed amongst the far more prevalent thinner fibers in the brain's white matter, are the ones that are crucial for the global

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[11] Unpublished data, personal observation (D.A.).

coherence and coordination of brain activity.[12] However, it is necessary to stress that the term "coordination" does not have here anything to do with the synchronization of the electrical activity of the cortex reflected in the slow waves of EEG (4 Hz delta waves), that rather tends to characterize unconscious states such as sleep, or some pathologic conditions such as Creutzfeldt-Jakob disease (and many others). It is broadly accepted that "synchronization" of the electrical activity of the brain cortex—this electrical activity obviously being only a (electro)physical result caused by multifaceted neuronal and glial activity—enables so called "disconnection" of the cortex from the extrinsic input of senses, as happens during sleep. The structures responsible for this are the so-called thalamocortical neurons—but only when the activity of these neurons is oscillatory (in contrast to their tonic activity, which is typical for a wakeful state). It is supposed that much faster oscillations (so called 40 Hz gamma waves) may play a role in the "binding" of sensory input crucial for awareness (see "Fourth Tenet: 'ON-OFF MECHANISM,'" page 18), but one may only speculate as to whether these oscillations have anything to do with the thickest nerve fibers of white matter. It seems probable, though, that for the normal conscious workings of the brain this organ must possess a more subtle "pacemaker" system that will act as a "watchman," keeping guard on the synchronicity, or—to put it better—the timing, of the brain's "workforce," but whose activity, as of now, cannot be detected electrically or electromagnetically (or, at least, not directly). Maybe this task (of keeping proper timing) is performed by some sort of servomechanism (in the synapses, perhaps?)—one that cuts off the passage of information when it does not reach its destination within the proper time? In contrast to well-known detectors of coincidence such as glutamate NMDA receptors (see below), it is conjectured that there may also exist, but have yet to be discovered, some detectors of "incoincidence." This would mean that such detectors are actively damping activity which is not time-coordinated.

As mentioned above, the thickest fibers might be considered the best substrate for pacemaking and time coordination when it comes to the activity of the brain centers, but are they really so? Maybe something incomparably faster should be acting in the brain to assure "real time" coordination and exchange of information within the brain?

Thus, by way of offering one last comment with respect to this second tenet (CONNECTIVITY), let us try to attend to what was embraced in

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[12] Though one cannot exclude the possibility of them simply representing extremely rare aberrant fibers that "went astray" during the formation and maturation of the brain.

parentheses at the end of the initial statement spelling out our first one (COHERENCE): namely, the remark "as if orchestrated." Though this music-related term, "orchestration," seems to be merely a figure of speech, there seems to be much more to it than just some feeling of elegance: it invokes an interesting quantum theory of mind. This is a neurophysiological attempt at visualizing a "conscious event," but one cannot exclude even a quantum-dynamic aspect to the latter. In thinking of the discrete character of a "unitary conscious event," one cannot avoid invoking the quantum-dynamic concept of wave-function collapse and the von Neumann—Wigner interpretation (to the effect that it is consciousness that causes the collapse of the wave function). The supposition is that one might find something analogous in the brain instantiation of consciousness, where this could turn out to be a process involving multiple discrete, momentary but separate, "collapse-of-wave-function-like" "conscious-events," glued together by memory, that make us feel the unity of mind. This is only meant as an analogy, and we have allowed ourselves to invoke the well-known theories of "quantum mind" here as they are so very intriguing, but whether or not there is a grain of truth in them is not something we are competent to ascertain. If (!) quantum-dynamic phenomena really do underscore consciousness, this surely puts all issues of "coherence," "coordination," and "orchestration" in a quite different perspective.

4. THIRD TENET: DETECTION OF COINCIDENCE

The tenet to which we now turn plays only a rather minor role in our article. Its main purpose is just to shift attention to the rather obvious need for the brain to have at its disposal a way of detecting synchronicity, and of ensuring the control of neural events in the brain with respect to their synchronicity. If we are looking to identify the "substrates of coincidence"—i.e. the elements of neuroanatomy and / or neurophysiology that might play a role in coincidence or manifest features of it, what surely first of all comes to mind are NMDA glutamate receptors (NMDA-Rs). In fact, these are the oldest and best known "devices" that serve this purpose. It is a receptor of glutamate (the most important excitatory neurotransmitter), belonging to a class of so-called ionotropic receptors of neurotransmitters—these in fact being ion channels that are opened after combining with the neurotransmitter. (Another class of neurotransmitter receptor consists of "metabotropic receptors," better referred to as receptors coupled with G-proteins.) NMDA is an extrinsic chemical compound, which is a more selective agonist of glutamate receptors than glutamate itself, and hence lends its name to this particular receptor.[13] Both ionotropic and metabotropic receptors are mostly present in the postsynaptic membrane (however, they may also be located on the presynaptic membrane), where they are activated by their cognate neurotransmitters ejected from presynaptic vesicles. Among many other ionotropic receptors for glutamate, as well as for other neurotransmitters, NMDA receptors (NMDA-Rs) possess a peculiar feature: namely, that the activation of NMDA-R (in fact an opening of the ion channel) requires not only the presence of (and a coupling with) glutamate, but also synchronic (!) depolarization of the postsynaptic membrane—i.e. the membrane of the postsynaptic neuron. In other words, excitation of the postsynaptic neuron by NMDA-R requires the fulfillment of two independent conditions: (1) depolarization of the postsynaptic membrane (due to the action of any other neurons connecting their axons with the neuron to be excited), and (2) a signal coming from the presynaptic neuron through secretion of glutamate from the presynaptic membrane. This means that at precisely the same time as the neurotransmitter (glutamate) is being released from the synaptic vesicles of the presynaptic neuron, the postsynaptic neuron must itself be in a state of depolarization (of the kind caused by the effect exerted on the postsynaptic neuron by the excitatory activity of other neurons). As a result, NMDA-R has long been known and referred to as a "detector of coincidence," and a quasi-natural realization of the logic gate "AND" in the brain.

In broader terms, NMDA-Rs act only if there is a *coincidence* of two events, whatever these events might be. For purposes of illustration, let us imagine a neuron in, say, the amygdala (part of the limbic system in the brain) of some animal—a rat—which is being taught to associate a ringing sound with an electric shock. A neuron (to be imagined) in the amygdala of the rat receives axons which are collaterals from the auditory pathway and from the spinal-cortical tracts that convey pain sensations (brought about by the electric shock). The NMDA-R in this neuron (let us say, on the synapse with the axon conveying the auditory signal) will excite the neuron only if the "sonic" signal approaches at precisely the same time as collaterals from the "pain tract" depolarize it. This "coincidence" will thus be "encoded," and since (assuming what is in fact very frequently the case in many regions of brain) NMDA-R is an element of the mechanism of so called "long-term potentiation" (or LTP), this (imaginary) neuron will, for

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[13] For the function of NDMA as an agonist, see Dariusz Adamek, Barbara Tomik, *Stwardnienie boczne zanikowe* (Kraków: ZOZ Ośrodek UMEA Shinoda-Kuracejo, 2005), 35–6.

a long time, have become an "encoder" of the association of the *two events* (electric shock and sound of a ring). This is, of course, a highly elementary model of the encoding of associations in the brain via NMDA-R (or, at least, where NMDA-R is an important contributing participant), but it is certainly reasonable to think that much more complicated associations between the moment-to-moment activities of different centers of the brain, such as would have to occur synchronically and would be required for the "realization" of conscious events, are also possible thanks to the complicity of NMDA-Rs (or other similar "devices" in brain). In fact, "decoding" and "encoding" of coincidence by neurons, of either this or other similar kinds, can be observed in many systems in the brain, and plays a role in a variety of functions (e.g., in the participation of neurons from the inferior olivary nucleus in the brainstem in the "decoding" of the direction from which sound approaches the ears—and hence in enabling identification of the source of a sound).

5. FOURTH TENET: "ON-OFF MECHANISM"

As we saw above, it is difficult to define what consciousness itself is. "Medical" or neurobiological texts tend to avoid offering any direct definition. Indeed, they might be said to be engaged in circumventing this problem by making assertions exclusively about its "dimensions" or "components." Philosophers, moreover, could be said to be involved in similar moves. According to the above-mentioned classification, we can discern two components of what, in the terminology already used here, would be called "access consciousness," that can be classified as forming its content: these are, on the one hand, its sensory, motor, memory, and emotion-constituted contents (for which the appropriate CNS and PNS systems are responsible), and, on the other, its subjectivity level—i.e. alertness, attention, awareness (of self and non-self—corresponding, in fact, to the "hard problem"). But in reality both of this aspects are connected with each another. Another example of an approach that can be taken is to be found in the assertion that consciousness is a multifaceted concept that has another two dimensions: arousal, or wakefulness (i.e., level of consciousness), and awareness (i.e., content of consciousness).[14] It is important to understand the difference between these two: arousal shows the wakefulness of a

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[14] Steven Laureys, Melanie Boly, Gustave Moonen, and Pierre Maquet, "Coma," in *Encyclopedia of Neurosciences*, ed. Larry R. Squire„ (Oxford: Academic Press, 2009), 2:1133–42, doi:10.1016/B978-008045046-9.01770-8.

given person, while awareness is their ability to perceive their environment. In a vegetative state, a person might well be awake but will still quite probably be unaware of themselves or their environment. Knowledge and understanding of the neural correlates of phenomenal consciousness will help us to say something more about the phenomenal states in such cases where we do not have access consciousness.

To understand what consciousness is,[15] it would probably be better (and easier) to grasp what states of impaired consciousness are—similarly, it is easier to define some particular disease than to define "health" per se. Nevertheless, to precisely define these is also by no means simple. In fact, there are several "levels" of loss in respect of access-consciousness: e.g. clouded consciousness, states of confusion, delirium, lethargy, obtundation, stupor, vegetative states, akinetic mutism, locked-in syndrome and coma (brain death can also be seen as the gravest loss of consciousness).

The definitions of these states of impairment to access consciousness (mostly practical or heuristic) can be found in the appropriate specialized texts in use by the medical profession, while any detailed discussion of these terms is, of course, beyond the scope of this article. Let us, then, concentrate our attention only on the "dualistic" or even tripartite aspect of the pathogenesis of comas—which may be caused either by bilateral diffuse damage to cortical or white matter (e.g., due to diffuse axonal injury after mechanical trauma), or by bilateral lesions of the upper part of the brain stem (the reticular formation of the brain stem), or, indeed, by bilateral lesions of the thalamus—especially those involving the medial and intralaminar regions. Simple deduction leads us inexorably to the conclusion that each and every one of the aforementioned "regions" is necessary for consciousness. (Incidentally, we may add here that lesions located caudally in the centers of the brainstem—the lower part of the pons or in the medulla—or other regions of the brainstem typically do not affect the level of consciousness. Consciousness is typically spared: e.g. in so called locked-in syndrome, involving lesions to the ventral midbrain or pons.) From the philosophical, ethical, and common-sense points of view, it is very important to know, for example, what are the neural correlates of consciousness in respect of coma and locked-in syndrome, as patient behavior can be very similar in both cases, but the corresponding states of consciousness (above all, in the sense of phenomenal consciousness) are very different.

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[15] A "joke-version" of this sentence might read: "To be aware of what consciousness is . . . "

Alertness (the state of wakefulness) is generally a prerequisite of attention and awareness (sleep is rather the exception here—see below). Both the so called subcortical arousal systems (upper brainstem, diencephalon, basal forebrain) and the cortical regions are critical for alertness. In the upper brainstem, norepinephrinergic, serotoninergic, dopaminergic and cholinergic nuclei play a role, as does the pontomesencephalic reticular formation, which is possibly glutamatergic. The list of other centers important for alertness is longer and includes: posterior hypothalamic nuclei (histaminergic and orexinergic), basal forebrain nuclei (cholinergic), rostral thalamic intralaminar nuclei (probably glutamatergic), and (medial) thalamic nuclei (also probably glutamatergic). All these centers (and diffuse projection systems related to them) have been mentioned above in Table 1. Moreover, some regions of the cortex, such as the frontal and parietal association cortices, as well as the anterior cingulate cortex, play a role in alertness. But is alertness always a prerequisite of consciousness—or, to be more specific, of self-awareness? Generally, sleep is regarded as being a state in which consciousness is either absent or diminished. However, in dreams we typically dream of ourselves in the "first person," which suggests the conclusion that our self—or, in this context, self-consciousness or self-awareness—is preserved during sleep and, of course, immediately after waking up, consciousness is fully restored. As a result, while recollecting our nocturnal dreams we do not normally feel any discontinuity of "self" (at least as regards the "core" of our self-consciousness) before, during, or after sleep: so in other words, continuity-of-self is (or seems to be) preserved.

Attention (another example, in fact, of something hard to define precisely) would appear to evince two distinct forms or aspects: (i) selective (or directed) attention, and (ii) sustained attention (which can be understood as vigilance or concentration, or else as non-distractibility). The following brain regions (above and beyond all the above-mentioned brain structures and systems relating to alertness inasmuch as it is necessary for attention) are involved in both forms of attention: the frontal (especially medial frontal) and parietal association cortices, the anterior cingulate cortex (cooperating with other limbic structures, and especially important for motivational aspects of both directed and sustained attention), the superior colliculi, the pretectal area and the pulvinar (with the parietotemporo-occipital cortex and frontal eye fields important in directing attention towards visual as well as auditory stimuli and other sensory modalities). It is thought that the basal ganglia and cerebellum also take part in directed attention, though we do have some doubts as regards the contribution of the cerebellum to cognitive tasks or functioning, since one of us (D.A.) had an opportunity to investigate a brain, belonging to a woman who had died aged 38, that was practically entirely devoid of cerebellum! (There were only miniature mushroom-like "vegetations," each a few millimeters in size, visible on both sides of the pons in an otherwise almost normal brain.) This lady had nevertheless managed to live a relatively normal life until some point in her adolescence, and though her intellectual capacities supposedly were not impressive, she did succeed in completing three years of study at primary school.[16]

As for awareness (in the sense of "conscious awareness," construed in our terminology as both access and phenomenal consciousness), a kind of working definition is that "it is our ability to combine various forms of sensory, motor, emotional and mnemonic information into an efficient summary of mental activity that can potentially be remembered at a later time."[17] As a result, what are known as "binding" and memory are phenomena that are of critical importance for "conscious awareness." Amongst the many noteworthy concepts and theories of binding is the idea that synchronized gamma oscillation (40 Hz) of groups of neurons plays a role.[18] In speaking of memory in this context, we are rather thinking of so called episodic memory and working memory. "Places" in the brain which seem to be implicated in self-awareness, self-reflection and introspection are located especially in the medial parietal region (the precuneus, the posterior cingulate in its vicinity, and the retrosplenial cortex).

In sum, the general conclusion that cannot be avoided here is that this neural "consciousness system" is rather complicated and large, and really—from a neurological point of view—"multicentered." But from the common-sense point of view we feel strongly, and know, that phenomenally we are one self, and that our consciousness is united. Philosophically speaking—outside of such things as Dissociative Identity Disorder—we are driven to assume that there is just one self, connected with one body (the brain). We shall continue this discussion in considering our next tenet.

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[16] Dariusz Adamek, Stanisław Żulichowski, and Józef Kałuża, "Long Survival with Cerebellar Aplasia and Degenerative Changes of CNS: A Case Report," *Neuropatologia Polska* 24, no. 1 (1986): 89–100.

[17] Hal Blumenfeld, *Neuroanatomy through Clinical Cases*, 2nd ed. (Oxford: Oxford University Press, 2010), 922.

[18] These oscillations are much faster than the slow delta oscillations (4 Hz) mentioned earlier, that seem to play a disconnecting role (cutting off the cortex from sensory input), and which are typical, among others, for the deep-sleep phase.

6. FIFTH TENET: REDUNDANCY

At the outset of this article, there was mention of the so called "eloquent" regions of the brain, where such a characterization relates to regions of the brain that, if damaged, engender obvious neurological manifestations—typically a deficit of function. As far as possible, neurosurgeons seek to avoid destroying these regions. It is, however, well known that there are in the brain much larger—indeed really vast—areas whose removal (typically due to tumor or epilepsy) does not manifest itself in any discernible neurological deficit and / or changes to behavior. Probably one of the best known examples is that described by Roger W. Sperry and Michael S. Gazzaniga, involving cases of split-brain persons.[19] This encourages one to conclude that the brain exhibits a remarkable degree of redundancy in respect of its structures—or, alternatively, that we do not have the appropriate tools for detecting the neurological deficits. Furthermore, there are many other cases one can point to in which—sometimes thanks to shockingly extensive removals of large parts of (or almost the entire) cerebral hemisphere (hemispherectomy[20])—consciousness was not affected and the patient's feeling of self was not disturbed! This may even speak in favor of the hypothesis to the effect that there could be more than one mind in the same individual. Such experiences pertaining to hemispherectomy also prompt one to ask questions about how much of the brain is in fact needed for consciousness, or even just for life.

A century ago, Korbinian Brodmann distinguished 52 areas of the brain cortex according to their cytological architecture. Though the division is still in use, in the case of most of these areas we cannot unequivocally ascribe any definite function (by linking a lesion to a specific clinical manifestation). Roughly a century after Brodmann's report, the situation turns out to be even more complicated. In the most up-to-date report, Matthew F. Glasser et al., using among other things sophisticated MRI-based tech-

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[19] See, e.g., Roger W. Sperry, "Hemisphere Deconnection and Unity in Consciousness," *American Psychologist* 23 (1968), doi: 10.1037/h0026839; Michael S. Gazzaniga, Richard B. Ivry, and George R. Mangun, *Cognitive Neuroscience: The Biology of the Mind*, 4th ed. (New York: W. W. Norton, 2014), ch. 4, "Hemispheric Specialization," 120–61; Thomas Nagel, "Brain Bisection and the Unity of Consciousness,"*Synthèse* 22 (1971), doi:10.1007/bf00413435; Tim Bayne, "The Unity of Consciousness and the Split-Brain Syndrome," *The Journal of Philosophy* 105, no. 6 (2008), doi:10.5840/jphil2008105638.

[20] In particular, extensive hemispherectomies have been performed to treat devastating drug-resistant epilepsy of the kind caused by, amongst others, Rasmussen encephalitis. See the original report of such cases by Theodore Rasmussen, Jerzy Olszewski, and Donald Lloyd-Smith, "Focal Seizures Due to Chronic Localized Encephalitis," *Neurology* 8, no. 6 (1958), doi:10.1212/WNL.8.6.435.

niques, managed to "parcel up" the human brain cortex into 180 separate and distinct areas within each hemisphere.[21] Again, we are far from understanding what particular function is subserved or contributed to in the case each of these, where the dimensions of such areas will obviously not exceed some mere tens of millimeters.

All the same, this report forces us to acknowledge that even though the plasticity of brain is quite remarkable, it is still probably the case that a loss of even just a small piece of the human brain (in this context, the cortex), though not explicitly manifested ("eloquent"), could somehow impact on the internal brain-mind machinery. Most of these 180 distinct regions are rather not "eloquent," but one may rightfully express some doubts regarding this proposition, arguing that whether they count as "eloquent" or not is potentially a matter of the investigative tool employed and / criterion applied. For example, we may imagine a small infarction that destroys one of those 180 regions found by Glasser et al., and which does not result in any neurological deficit even after meticulous clinical examination. But can one really then say that this proves that this particular region was actually redundant? A mistake of evolution? A freak of nature? If we approach this from a teleological perspective, we should obviously then ask what "the purpose" of such a piece of the brain could have been, given that it seems not to be needed for anything. But if we abandon the teleological perspective, it is hard to avoid conjecturing that this particular fragment of brain cortex, or rather the lack of it (inasmuch as it has been destroyed by infarction, mechanical trauma or neurosurgical intervention), might well prove to possess even a vital role ("purpose") in certain highly peculiar yet nevertheless important circumstances: for example, when a particular decision has to be made by the individual in question. Indeed, it might even be life-and-death decision. So one may ask whether any piece of brain can truly be regarded as "ineloquent" (or unimportant).

On the other hand, invoking teleology once again, it might conceivably be the case that many, if not most, of those 180 regions of the brain cortex are simply "pre-prepared" for future tasks or circumstances, and not necessarily even just those pertaining to some particular individual, but rather ones internal to the generic future of mankind as whole. Maybe this false "redundancy" in respect of brain structure indicates that we do not know how to optimally use our brains, and this could be further confirmation of hypotheses to the effect that we are only able to effectively

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[21] Matthew F. Glasser, Timothy S. Coalson, Emma C. Robinson, et al., "A Multi-modal Parcellation of Human Cerebral Cortex," *Nature* 536, no. 7615 (2016), doi:10.1038/nature18933.

use a small portion of our brains. Yet it seems that the likely explanation for the existence of those 180 (and who knows how many more, in fact?) regions is this: that most of them are working "silently" all the time, in an unconscious mode, observing and analyzing and trying to predict the immediate future "state of our environment," and yielding up to conscious access only particular "chosen" elements of reality—ones that happen to be important (or seem so) at a particular moment, even perhaps for just a fraction of a second. As a result, it seems probable that most of those "ineloquent" parts of the brain cortex (surely connected functionally with the subcortical ganglia) are in fact the neurobiological "substrate" of what has been proposed in connection with the notion of a "global neuronal workspace."[22] In this context, a crucial question (which we are not in a position to try to answer) is where the brain mechanism for conscious access to this workspace might be located, and what it might consist in.

Of the innumerable questions concerning the relationship between the brain and consciousness (and the mind in general) that are or can be asked—and passing over so called psychosurgery, which is now regarded as rather inhuman (though its most famous protagonist, Egas Moniz, was once rewarded with Nobel Prize)—let us try to pose a provocative question: is a neurosurgeon, removing a part of the brain for any reason, in fact removing a part of the conscious mind? Also, could a biopsy of the brain be of use not only for diagnosing "somatic" diseases, but also to tell us something about the intrinsic mental, cognition-related, phenomenal characteristics of the person being examined? Even if the smallest piece of the brain were to be recognized as extremely valuable (as with, maybe, a piece of the retina), we know that a large-scale hemispherectomy need not unequivocally affect consciousness.[23] In contrast to this, as is well-known, incomparably smaller lesions to the brain stem (e.g., involving some nuclei in the medulla oblongata[24]) can be devastating with regard to brain

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[22] Stanislas Dehaene, *Consciousness and the Brain: Deciphering How the Brain Codes Our Thoughts* (New York: Viking, 2014).

[23] James Blackmon, "Hemispherectomies and Independently Conscious Brain Regions," *Journal of Cognition and Neuroethics* 3, no. 4 (2016), http://jcn.cognethic.org/jcnv3i4_Blackmon.pdf.

[24] The medulla oblongata controls autonomic functions. We would not be able to live without the medulla, because of the innumerable vital tasks it performs relating to the regulating of blood pressure and breathing. As a part of the brain stem, it also aids the transfer of neural messages from the brain to the spinal cord. Cf. Rolland S. Parker, *Traumatic Brain Injury and Neuropsychological Impairment: Sensorimotor, Cognitive, Emotional, and Adaptive Problems of Children and Adults* (New York: Springer, 1990), 39–40, doi:10.1007/978-1-4612-3398-5.

function, while centers in the brain stem, inter alia, are themselves critical for life itself and, as a consequence, also for both phenomenal and access consciousness. Moreover, there is some preliminary data that tentatively suggests that appropriate stimulation of certain tiny tracts involving the medulla and cervical spinal cord may be helpful in treating cases of persistent vegetative state (PVS).[25]

7. Concluding Remarks

Summarizing this complex topic, we should note the following:

1. Not every region of the brain is "equi-valued" with regard to the most simple (and most vital) functions; this is why we frequently have recourse to the notion of "eloquence" when discussing those regions where damage leads directly to neurological deficit (like paralysis or aphasia), and consequently to impaired thinking and behavior on the part of persons. Nevertheless, if we recall the already mentioned report of Glasser et al., then we must assert that the structural patterning of the brain cortex cannot be for nothing! It must have developed either evolutionarily or, possibly, through some sort of teleological "design," making us what we are, with our whole—phenomenal and access—consciousness. If many of these 180 regions are in fact not "eloquent," then what do they exist for? It might be that some of them are something like spare or supplementary ("reserve") brain areas, prepared (by evolution) to provide additional "computational capacity" such as would enable the conscious mind and brain to cope with new and unexpected, or impossible to predict, tasks, or to allocate temporarily or permanently some particular memory and / or function to, or, indeed, to unconsciously perform continuous analysis of the signals coming both from within our body and from our environment. The brain, supposedly, works most effectively in its entirety, but is consciousness in fact the sort of feature of our mind that can be either present or absent? Rather not. Consciousness can exhibit many "levels," and one cannot exclude the uppermost of these being reached by only a small minority of human beings. Maybe it is only in their cases that the brain is truly using its full "computational capacity." However, this would seem to

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[25] Tetsuo Kanno, Isao Morita, Sachiko Yamaguchi et al., "Dorsal Column Stimulation in Persistent Vegetative State," *Neuromodulation* 12, no. 1 (2009), doi:10.1111/j.1525-1403.2009.00185.x.

involve a rather over-extended conception of the meaning of the term "consciousness," and perhaps may more properly be taken instead to refer to degrees of what is colloquially talked about as "insight." But maybe "insight" is itself just an "extension" of consciousness.

2. The various states of consciousness are the result of an interaction between multiple brain systems. To show this in an exemplary way, we may point to the fact that while one system occurs in the brain-stem reticular formation and is connected with (i.e., sends projections to) the cortex via thalamic nuclei, others are composed of brain-stem and some other specifically located nuclei (including in the hypothalamus), which release neurohormones to various brain regions via ascending projections (so called diffuse projecting systems).
3. It is rather obvious that there is no single cortical area that "specializes in," or is designed for the maintenance of, the whole of consciousness. Almost all cortical interconnections have to be disrupted before someone can lose consciousness (provided that "centers" such as the thalamus and the reticular formation remain intact). Hence, one may conclude that all, or almost all, cortical areas are involved in the consciousness system as a whole; yet one would do well to remember the evident fact that even removal of practically an entire hemisphere does not cause a loss of self-awareness.
4. The consciousness system is a diffuse yet organized neuronal system located in the brainstem, diencephalon, and cerebral hemispheres with diffuse reciprocal connections. Although it is complex, and still very much remains to be explored, it can be divided into a few groups of structures for the purposes of our current understanding. These include (i) nuclei of the brainstem reticular formation, hypothalamus, basal forebrain, and thalamus; (ii) the ascending projection pathways; (iii) widespread areas of the cerebral cortex.
5. Anatomical connectivity is not enough, and any sort of "conscious event" will most probably also depend on "synchronicity" (timing) of action with respect to circuits and systems (especially diffuse projecting ones). Here, we boldly propose the following hypothesis: that in the context of the role played by any neural solutions with regard to the detection of synchronicity (e.g., NMDA glutamate receptors, which are the best known ones in this regard), there might exist quasi-active mechanisms for blocking neural inputs that do not fall within certain rather narrow time limits. Such hypothetical mechanisms would, on the one hand, serve as "safeguards" against "information overload," enabling, say, a given neuron to optimize its most discrete moment-to-

moment task (for example being an element of some consciousness-related system or other); on the other hand, though, such "safeguarding" or "time-discipline-enforcing" mechanisms could also limit the depth of our insights into reality (in the sense of the level of our awareness of our environment).

6. The brain, as a phenomenon, quite simply surely merits unbounded reflection on our part. Examining it in whichever way we choose—e.g., using fMRI imaging—will always cause us to step back in sheer awe and admiration. More particularly, we may also presume to assert that, in its (morphological, not functional) hemispherical symmetry—which is that of an organ that can bring to bear love, compassion and mercy, but can also carry out the most fearful, awesome and heinous deeds—the brain can call to mind the verse of the famous poem by William Blake in which the poet invokes a "fearful symmetry" (that of a tiger). Having especially in mind a picture of the brain on a monitor of a MRI tomograph, a free parody of the latter might take the following form: "Brain, o brain thus burning bright / Sparkling dots in screen on sight / What immortal hand or eye / Dare frame thy fearful symmetry?" Such an attempt at "poetical" parody acknowledges the reverence that we feel, when by whatever method of investigation—be it instrumental (e.g., autopsy) or purely mental (e.g., philosophical)—we approach the awesome enigma of the "mind-brain" (or "brain-mind").
7. One highly important question is this: what sort of damage can be expected to result in loss of consciousness? From clinical and experimental evidence, we know that the functional integrity of the upper pontine and mid-brain reticular formation, intralaminar nuclei, midline nuclei of the thalamus, reticular thalamus nuclei, and the bilateral cerebral cortex are all critical to the maintenance of consciousness. To summarize, there are three primary mechanisms that can impact upon the consciousness system: (i) lesion of the brain-stem reticular activating system or bilateral posterior hypothalamus, (ii) bilateral disruption of ascending projections at the level of the thalamus, and (iii) diffuse bilateral hemispheric cortical lesion. Although consciousness is affected in each case, different degrees of interruption result in different consequences, as was shown before.
8. By way of a final conclusion, we may wonder that it is poetry, that "faculty" we have recourse to when seeking to express the inexpressible, that can describe in the best way the brain on the stage of consciousness. But that need not imply that the stage (as in a theater), and its "authors" (as the "centers" of a moment-to-moment perform-

ing of plays) are something "real," while the scenario and the written play (e.g., a drama), and, by analogy to these, also consciousness, are something virtual. Rather, as of today, we can say that between the conscious mind and the brain there exists a kind of emergent (correlational) dependence, while the exact neuronal mechanism underpinning this dependence remains unknown.

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