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The Global Neuronal Workspace as a multilevel model of conscious processing

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Debates in consciousness science increasingly question whether computational functionalism is sufficient to explain conscious processing. We summarize three core features of the Global Neuronal Workspace (GNW) theory that highlight the multilevel architecture of conscious processing, extending from cellular and molecular mechanisms to large-scale network dynamics. On this interpretation, GNW is not a functionalist computational theory, unlike the Global Workspace theory, with which it is frequently conflated.

The insufficiency of functionalist models

An important issue in 'theories of consciousness' is whether 'functionalist' computational models suffice to account for conscious processing (e.g., [1]). This issue is important because it concerns the use of computational models to understand physical reality, including life and conscious processing. Since the physicalist physiology program associated with Helmholtz, du Bois-Reymond, and Brücke, biological processes have generally been treated as governed by physical and chemical forces, and there has been wide scientific agreement that these 'forces' also include conscious processing and might, in principle, be described in mathematical terms down to the lowest physical level. Yet a mathematical or computational description of the different functional levels of conscious processing does not by itself imply a functionalist account such that conscious processing might be considered independently from its physical basis. It is therefore more appropriate to refer to different organizational levels of reality characterized by diverse modes of computation. Our view is that, in living organisms, as a consequence of biological evolution, physical reality exhibits a deeper multilevel organization than in inanimate objects, including entangled interlevel connections required for their integration from molecules to social relations. Against this background, the molecular level appears largely undervalued in current theories of consciousness, which tend to focus primarily on the cognitive functional dimension.

One may recall Claude Bernard's distinction between structure, function, and their relationships in living organisms—including conscious processing. If the physical reality of living organisms is multilevel, with different levels of organization, each describable in Marr's computational, algorithmic, and implementation terms, the first two terms would correspond to Claude Bernard's 'function'. The issue, then, is whether it suffices to take into account exclusively these two terms (i.e., computational and algorithmic) for an adequate description of physically real living systems. Although a long physiological tradition, cognitive functionalism, and mainstream artificial intelligence (AI) converge on a positive answer, recent arguments support the opposite [1–3].

These arguments are consistent with our aim to elaborate 'formal organisms' that can pass cognitive tasks and can be experimentally tested at their multiple levels of organization. The complex set of constraints that make possible and effective the explanatory and predictive insights of the model itself is crucial; in particular, the cognitive upper level of organization is not sufficient by itself to explain and make possible the replication of conscious processing [4].

We summarize the following three features of the Global Neuronal Workspace (GNW) theory that underline the multilevel organization of conscious processing, particularly emphasizing the critical role played bottom-up by the molecular level.

Global Neuronal Workspace is a multilevel model of conscious processing

In its original 1998 formulation [5], GNW theory unambiguously aims to account for conscious processing on the basis of its physical, neurobiological implementation. GNW theory is originally immune to any form of computational functionalism: it belongs to the so-called 'meat machines' [1]. Notwithstanding some differences in its subsequent formulations (reviewed in [6]), the 1998 version of GNW theory, which includes explicit implementation from molecules, neural circuits, and global modulation up to cognition, is, for us, the unique formal account to consider. Accordingly, GNW theory clearly differs from the Global Workspace Theory (GWT), a psychological, disembodied model open to functionalism (Box 1). Moreover, GNW is distinctive in explicitly integrating Marr's three levels and, in particular, in relying on the 'hardware', from the molecular level up to connectomics and the cognitive level.

Historically, GNW theory emerged from a series of attempts to model cognitive functions bottom-up, from molecules to cognition [9–11]. It began with a model of learning temporal sequences by selection, whose basic components are 'molecular units' forming mutually inhibiting clusters of synergic neurons and bundles of synapses involving allosteric receptors [9]. Subsequent models of the Wisconsin Card Sorting, and later of the global workspace in effortful tasks, proposed that variable 'pre-representations' were spontaneously

Box 1. The GNW theory

The GNW theory of consciousness takes root in the actual neural structures that produce conscious processing, in particular, the neuronal structures that provide reward and vigilance inputs via specialized neurotransmitter pathways. This connection is such that GNW theory makes sense only on the basis of the biological and molecular organization of the conscious organism.

Notwithstanding some successive differences, the unique formal version of GNW theory is that originally described in [6]. In short, GNW theory is a neuroscientific theory with explicit implementation from molecules, neural circuits, and global modulation to cognition. On that formal basis, modeling has been further developed for special tasks or further discussed and developed. GNW theory thus clearly differs from the GWT, which is a psychological model open to functionalist interpretations. Also, anatomically, the definition of GNW by Dehaene, Kerszberg, and Changeux [5] includes a neuronal granularity absent from Baars' GW. The GNW relies on an elaborate network of cortical pyramidal neurons with long-distance cortico-cortical and subcortical connections able to broadcast *selective information* at the brain scale [6]. While according to Baars terms (in his 1988 book *A Cognitive Theory of Consciousness*), the neural base of GNW is an 'Extended Reticular Thalamic Activating System' with neurons 'projecting *diffusely* […] to the cerebral cortex' [7]. As originally formulated, GNW theory is not disconnected from the living, biological subject, and it is not a disembodied computational account of conscious processing. In fact, the major benefit of GNW theory is to promote the identification of the aforementioned pathways, the concerned cerebral circuits, and their specific molecular receptors leading to efficient medications for neuropsychiatric diseases [8].

generated and selected by reward through allosteric switches [5,9] within a well-defined 'global neuronal network'. In its mature formulation, this GNW network is explicitly assumed to consist of distributed, heavily interconnected neurons with long-range axons, operating on top of a set of specialized, modular, and nonconscious perceptual, motor, memory, evaluative, and attentional processors. We have previously mentioned 'connections providing excitation or inhibition (via intermediate processing inhibitory interneurons)' [5] and further stated explicitly [11] that 'the presence of inhibitory interneurons becomes necessary to maintain a self-sustained representation within the GNW in the absence of sensory input'. Finally, at a higher level, GNW theory considers the role played by evaluation reward circuits as a necessary condition for making 'valenced' conscious processing and thus subjective experience accessible [12]. GNW theory thus firmly argues that three fundamental features—multilevel bottom-up organization, inhibitory interneurons, and evaluation reward circuits—are necessary for conscious processing in contrast to a simple functionalist process.

Yet this does not exclude, in principle, the possibility of different (e.g., artificial or lower organisms) modes of conscious processing: while it explicitly qualifies GNW theory as a multilevel computational model, it outlines that 'consciousness' is an ambiguous term that needs to be specified and operationalized.

Developmental epigenesis of Global Neuronal Workspace

GNW theory also recognizes the importance of both ontogenetic development and interaction with environmental factors for a full conscious experience. The GNW develops stepwise after birth (see [12,13]). A lowest level of 'minimal consciousness' is proposed to be present in 25- to 30-week preterm fetus, followed by a 'recursive consciousness' in the newborn infant, explicit 'self-consciousness' at the end of the second year, and lastly 'reflective consciousness'—including theory of mind and full conscious experience—in children aged 3–5 years.

At birth, all major long-distance fiber tracts are already in place, although still immature, and an electrophysiological signature of conscious processing homologous to adult GNW ignition has been recorded in 5- to 15-month-old babies. Yet, over the extended process of postnatal development, epigenetic evolution in brain connectomics takes place, shaped by the extended interactions between the brain and the physical, biological, and, most of all, the social and cultural environment through a 'Darwinian' mechanism of synaptic selection [9]. These stored long-term memories, which include oral and written language learning abilities, arguably shape the subjective experience of any individual. This multifactorial and multilevel epigenesis of GNW confirms that it cannot simply be reduced to functionalist computations at the cognitive level. Furthermore, at variance with artificial systems, valenced experiences processed and classified by the brain appear ultimately crucial for the subject's 'full conscious experience' of social and cultural life.

Medical and social relevance of Global Neuronal Workspace theory

As stated in the original paper on GNW theory [5], it 'predicts that workspace neurons are the specific targets of projections from neuronal structures that provide reward and vigilance inputs, presumably via specialized neurotransmitter pathways'. GNW theory further differs from functionalist models, first and foremost, for its biological and pharmacological realism down to the molecular level. A major benefit of GNW theory is that it promotes the identification of the aforementioned neurotransmitter pathways, the concerned cerebral circuits, and their specific receptors, potentially facilitating the development of efficient medications for neuropsychiatric diseases [8]. Access to conscious processing in the human brain requires a rich and dedicated biochemical context that is notably absent from the current AI attempts to produce artificial conscious processing [12] (Box 2).

Another benefit of GNW theory derives from its multilevel description of the brain. The trillions of synaptic connections in our brain create an astronomical number

Box 2. The biochemical roots of conscious processing

Proteins are the critical molecular components of biological organisms. These macromolecules are made up of strings of amino acids, which fold in a highly sophisticated organization able to create specific binding sites for a broad diversity of ligand, including metabolites, neurotransmitters, lipids, and DNA. The protein components of the organism, which contribute to brain metabolism and regulation, are highly heterogeneous (reviewed in [8]). These components also impact the control of the states of consciousness and their diversity, as illustrated by the global chemical modulation of sleep and wakefulness or the diversity of drugs that cause altered states of consciousness. As a result, conscious processing in the human brain requires a rich and dedicated biochemical context that is widely absent from the current AI attempts to produce artificial conscious processing, namely, computers have no pharmacology and no neuropsychiatric diseases [8]! While the crucial role played by pharmacological factors in human consciousness does not logically exclude the fact that AI systems may instantiate alternative, nonhumanlike forms of consciousness, the strict molecular and pharmacological conditions for biological consciousness may help clarify which factors current AI systems lack that may be taken as inspiration for advancing toward more realistic artificial forms of conscious processing.

of possible combinations. In interacting with itself and its social environment, the human brain is confronted with the use of a limited and relevant number of them to generate cerebral representations on psychological time scales. We have suggested [12] that the human brain has the ability to develop 'rules' that limit, from top to bottom, the number and nature of accessible brain representations and act as a kind of 'acquired neural framework'. The hypothesis is that these epigenetic traces define rules of conduct, which, in the GNW of individual subjects, mobilize the prefrontal cortex. This framework creates a space for ensuring that the evolution of our social structures, global education, and cultures interact constructively with the neural architectures of our brains to benefit the survival of humanity with an enhanced quality of life.

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