

## Regenerative Process in Life and Mind

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*There seems to be in us a sort of affinity to musical modes and rhythms, which makes some philosophers say that the soul is a tuning, others, that it possesses tuning.* —Aristotle<sup>1</sup>

*When we seek a mechanistic explanation of the various rhythms of any and all living systems, we eventually come to conceive of their activities in terms of circularities in the nexus of their causation.* —Warren McCulloch<sup>2</sup>

**ABSTRACT:** The functional organization of the nervous system is discussed from the standpoint of organizational closure and regenerative process in order to draw parallels between life and mind. Living organization entails continual regeneration of material parts and functional relations (self-production). Similarly, dynamic stability of informational states in brains may entail coherent self-regenerating patterns of neural signals. If mind is the functional organization of the nervous system, then mental states can be seen as switchings between alternative sets of stable, self-regenerative neural signal productions. In networks of neurons, signaling resonances can be created through recurrent, reentrant neural circuits that are organized to implement a heterarchy of correlational operations. Neural representations are dynamically built-up through an interplay between externally-impressed, incoming sensory signals and internally-generated circulating signals to form pattern-resonances. Semiotic aspects of resonance states involve semantic sensori-motor linkages to and through the external environment and pragmatic linkages to evaluative mechanisms that implement internal goal states. It is hypothesized that coherent regenerative signaling may be an organizational requirement for a material system to support conscious awareness. In this view general anesthetics and seizures abolish awareness by temporarily disrupting the organizational coherence of regenerative neural signaling.

### REGENERATIVE PROCESSES IN LIFE

We attempt to bring together some fundamental concepts that are common to an organizational view of life and mind. Both the material organization that characterizes life and the configurational, informational organization that characterizes mind involve at their root the notion of regenerative organization. Regenerations of parts and reproductions of whole organisms are the central concepts that define living

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systems.<sup>3-6</sup> Regenerative processes in which energy flows, material parts, and functional relations are continually recreated from system-actions permitting energetically open organizations to continually reproduce their internal relations, thereby maintaining their identities over time.

Regeneration of relations between material parts is the basis for self-construction and self-repair. This idea has evolved in a number of related forms. Some theorists have focused on metabolic descriptions that deemphasize the role of biological symbols, for example, autopoietic models,<sup>3,6,7</sup> reaction networks, and autocatalytic networks.<sup>8</sup> Others have placed genetic codes and their role in constraining dynamics at the center of these processes, for example, genetic plans and phenotypic constructions in self-reproducing systems,<sup>9</sup> metabolism–repair systems,<sup>4</sup> and symbol–matter systems.<sup>10,11</sup>

These differences notwithstanding, to the extent that structures and functional organizations are continually regenerated by internal mechanisms, some degree of material and functional closure is achieved. This closure, or internal causation, in turn creates domains of relative structural and functional autonomy wherein invariant structures and functional relations are preserved by virtue of internal rather than external processes. Living organization entails this closure of production of material parts and relations (structural and functional self-causation), that is, the system reproduces its parts and its whole.<sup>12</sup> Closure creates an inside that is self-produced and controlled from within, and an outside realm of relatively contingent processes that are not produced by the self-production loop. Closure and autonomy are always only partial for biological systems that are in constant interaction with their environs: for an energetically-open system there is always the necessity of material exchange; for an informationally-open system there must always be some contingent interaction with the external world.

### REGENERATIVE PROCESSES IN NERVOUS SYSTEMS

From the beginnings of Western natural philosophy, both life and mind have been seen in organizational terms, particularly in Aristotle's concept of *psyche*.<sup>13,14</sup> It is therefore not surprising that conceptions of the coherent functional organization of nervous systems have developed in parallel with those for biological organisms. Anatomically, the nervous system consists of a huge multiplicity of transmission loops: recurrent multisynaptic connectivities, reciprocal innervations, and reentrant paths.<sup>15-17</sup> Virtually every neuron in the system is part of a signaling cycle, providing inputs to and receiving inputs from other elements in the network. These signaling cycles manifest themselves physiologically in terms of reciprocal activations, reverberations, and more complex, history-dependent modes of activity.<sup>18,19</sup> Theoretical neuroscientists have generally believed that this recurrent organization is essential to the operation of the nervous system as an informational system, on both macroscopic and microscopic levels. Within individual neurons, a host of regenerative action-recovery cycles subserve synaptic action as well as the generation and transmission of action potentials. Thus, many of the first formal models of neural networks dealt with the stability properties of closed cycles of excitation and inhibition,<sup>20</sup> of pulse-coded "nets with circles",<sup>21,22</sup> and assemblies of oscillators.<sup>23</sup>

Psychology was accordingly formulated in terms of reverberant signaling loops.<sup>24</sup> In this framework, mental states could be seen as alternative eigenstates of a large, dynamic system.<sup>25,26</sup> At a few junctures, formal relations between metabolic networks and recurrent neural networks were considered.<sup>3,6,8,20,27-30</sup>

Nervous systems are also informationally-open systems; in addition to internally generated activity, they also interact with their environments through their sensory inputs and motor outputs. Together these internal and external linkages form percept-action loops that extend through both organism and environment.<sup>31</sup> Thus, both the internal structure of the nervous system and the structure of its transactions with the environment involve circular-causal loops.<sup>32,33</sup> The central metaphor of cybernetics was inspired by this cyclic image of brain and environment, where internal sets of feedback loops themselves have feedback connections to parts of the environment.<sup>2,34-37</sup>

On a very high level of abstraction the nervous system can be seen in terms of many interconnected recurrent pathways that create a series of neural signaling *resonances* (FIGURE 1). Sensory information comes into the system through modality-specific sensory pathways. Neural sensory representations are built up through basic informational operations that integrate information in time by establishing circulating patterns that are continuously cross-correlated with incoming interactions (i.e.,

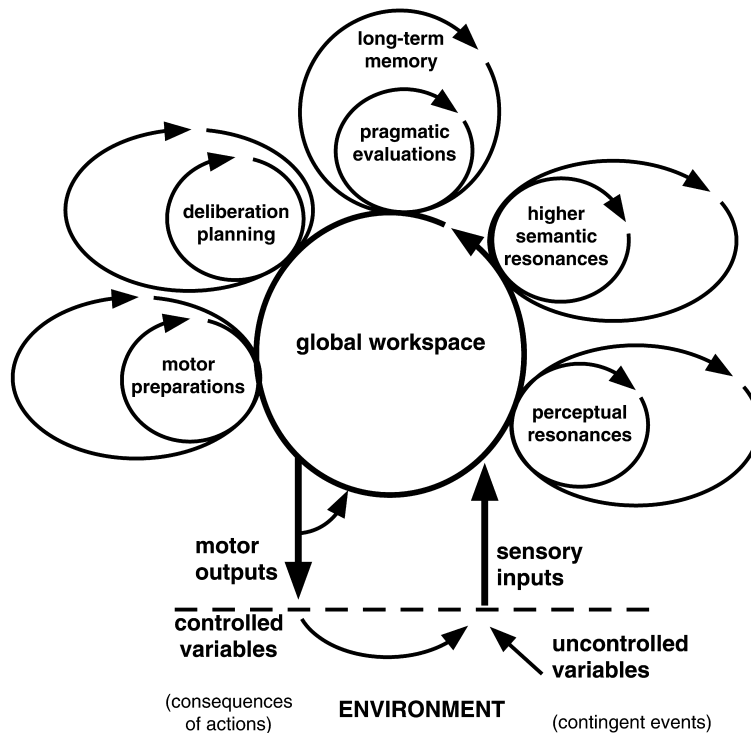


FIGURE 1. The brain as a set of internal and external resonant loops.

bottom–up/top–down interactions). When subsequent sensory patterns are similar to previous patterns they are built up and inputs are integrated over time. When subsequent patterns diverge from previous patterns, new dynamically-created *templates* are formed from the difference between expectation and input. The result is a pattern-resonance. Tuned neural assemblies can provide top-down facilitation of particular patterns by adding them to circulating signals. This conception of the brain as a series of *adaptive resonances* has been elaborated in great depth by Grossberg and colleagues,<sup>38,39</sup> whose adaptive-resonance models qualitatively account for a wide range of perceptual and cognitive phenomena. Various attempts have been made to locate neural resonances in particular reentrant pathways, such as thalamocortical and cortico-cortical loops.<sup>40,41</sup>

For the most part, neural resonance models have assumed that the underlying neural representations of sensory information utilize channel-coded, input features and neural networks with specific, adaptively modifiable connection weights. However, a considerable body of psychophysical and neurophysiological evidence exists for many other kinds of neural pulse codes in which temporal patterns and relative latencies between spikes appear to subserve different perceptual qualities.<sup>42–44</sup> For example, patterns of interspike intervals correspond closely with pitch perception in audition<sup>45</sup> and vibration perception in somatoception.<sup>46</sup> Neural resonances can also be implemented in the time domain using temporally-coded sensory information, recurrent delay lines, and coincidence detectors.<sup>19,47</sup> In addition to stimulus-driven temporal patterns, stimulus-triggered endogenous patterns can be evoked by conditioned neural assemblies.<sup>48</sup> Networks of cognitive timing nodes that have characteristic time-courses of activation and recovery time have been proposed as mechanisms for sequencing and timing of percepts and actions.<sup>49</sup> Roy John has proposed *hyperneurons* as coherent temporal, spatially-distributed and statistical orders consisting of stimulus-driven and stimulus-triggered patterns that provide the neural substrates for global mental states.<sup>50–55</sup>

Build-up loops and their associated resonance-processes can be iterated as one proceeds more centrally into successive cortical stations. Once sensory representations are built up in modality-specific circuits (e.g. perceptual resonances in thalamic and primary sensory cortical areas), they become available to the rest of the system, such that they can activate still other neural assemblies that operate on correlations between sensory modalities (e.g. higher order semantic resonances in the association cortex). Subsequent build-up processes would then implement correlational categories further and further removed from sensory specifics. These resonances can also involve the limbic system, which could then add evaluative components to circulating sets neural signal-patterns (pragmatic evaluations). Similarly circulating patterns could activate associated long-term memories, which in turn facilitate activation of other assemblies.

The global interconnectedness of cortical and subcortical structures permits widespread sharing of information that has built-up to some minimal threshold of global relevance, in effect creating a *global workspace*.<sup>56</sup> The contents of such a global workspace would become successively elaborated, with successive sets of neurons contributing correlational annotations to the circulating pattern in the form of characteristic pattern-triggered signal tags. Such tags could then be added on to the evolving global pattern as indicators of higher-order associations and form new

primitives in their own right.<sup>57</sup> Neural signal tags could signify semantic content (i.e., relationships to sensory and motor linkages with the external world) and pragmatic content (i.e. relationships to hedonic, motivational, drive states and system-goals) by virtue of the connections of the neural assemblies that produced them to sensory, motor, and limbic populations. Rather than a feed-forward hierarchy of feature-detections and decision-trees, the staple of traditional computational models, the system would more resemble a heterarchy of correlational pattern-amplifiers in which neural signals are competitively facilitated and stabilized to produce one dominant pattern that ultimately steers the behavior of the whole.

### ORGANIZATIONAL SUBSTRATES FOR CONSCIOUS AWARENESS

Throughout the history of neuroscience, there has been an abiding, if sometimes covert, interest in the relationship between neural processes and conscious awareness.<sup>58</sup> During the last decade there has been a revived public discussion of the neural correlates of experience.<sup>59–61</sup> One wants to explain the basic structure of normal waking experience including changes induced by different kinds of natural stimuli, electrical stimulation, general anesthetics and other chemical agents, sleep states, lesions, comas, and seizures. In keeping with prevailing approaches to brain function, some have sought to locate particular neural circuits and subpopulations responsible for particular experiences (neural *seats of consciousness*). However, a more comprehensive, organizational basis for consciousness is possible. In this view, some organizations of matter are capable of supporting informational operations that persist in a coherent way over time, and that these informational coherences are necessary and sufficient for conscious awareness. This view, in various forms, has been proposed by a number of scientists and philosophers at various times in the past. Most abstractly, organizational constraints could be autopoietic self-productions of neural signals<sup>3,6,29,62</sup> or organizational closures.<sup>63,64</sup> Intrinsic rhythms and global synchronization patterns were considered early on as possible organizational substrates,<sup>65–67</sup> but their relationship to the contents of conscious awareness has always been equivocal.<sup>68</sup> John has proposed anatomically-distributed coherent, statistical organizations of neuro-glial activity (hyperneurons) as organizational substrates,<sup>19,52</sup> but distributed patterns are experimentally difficult to detect. Grossberg holds that every perceptual and cognitive distinction of which we are aware must be part of an adaptive resonance process in which alternative patterns are competitively selected and has specific models for liminal and subliminal aspects of visual and auditory perception.<sup>39,69</sup> Neural architectures may be arranged such that only some kinds of (correlated) patterns can be effectively amplified in global regenerative loops such that they become self-sustaining. This would then place additional neural coding constraints on the contents of awareness.<sup>60</sup> At best, testing these more specific hypotheses is presently very difficult, in part due to our current lack of adequate accounts of how central neural circuits represent and handle information.

Some basic features of experience may be explicable in this framework. General anesthetic agents may abolish conscious awareness because they alter membrane threshold-recovery dynamics<sup>70–74</sup> that may be essential for the temporal coherence of regenerative signaling. Epileptic seizures disrupt awareness because waves of

neural discharges supplant normal coherent patterns of neural activity. Regenerative self-production loops create functional boundaries that demarcate those signals created by the system (inside) from those patterns that are caused by external perturbations (outside), that is, they are contingent upon (sensory) interactions with the external world. Phenomenally, contingent processes are experienced as sensations whereas self-generated sequences of productions are experienced as thoughts. When parts of the external environment come under the reliable, automatic control of the nervous system (controlled variables), they generally cease to be experienced as sensations. Phenomenal boundaries follow these functional boundaries of control and contingency, as when one uses a stick to sense surrounds: one feels the bounds of one's body at the distal end of the stick rather than at one's hand. The properties of circular-causal loops may thus explain a major feature of the structure of experience—the division between thoughts and sensations.

Organizational conceptions of mind, brain, and consciousness fit naturally into a hylomorphic view<sup>14,75</sup> in which the functional organization that constitutes a mind is inseparably embedded in the material substrate that constitutes a brain. Material, formal, functional, and experiential properties constitute complementary aspects of underlying material substrates.<sup>75</sup> To the extent that regenerative signaling organizations are in fact essential for stable and coherent neural, mental, and experiential states, then a common organizational requisite exists both conscious awareness and life itself.

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