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Physics of Life Reviews 10 (2013) 85–94

PHYSICS of LIFE reviews

www.elsevier.com/locate/plrev

Review

Dissipation of 'dark energy' by cortex in knowledge retrieval

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Available online 9 January 2013

Communicated by L. Perlovsky

Abstract

We have devised a thermodynamic model of cortical neurodynamics expressed at the classical level by neural networks and at the quantum level by dissipative quantum field theory. Our model is based on features in the spatial images of cortical activity newly revealed by high-density electrode arrays. We have incorporated the mechanism and necessity for so-called dark energy in knowledge retrieval. We have extended the model first using the Carnot cycle to define our measures for energy, entropy and temperature, and then using the Rankine cycle to incorporate criticality and phase transitions. We describe the dynamics of two interactive fields of neural activity that express knowledge, one at high and the other at low energy density, and the two operators that create and annihilate the fields. We postulate that the extremely high density of energy sequestered briefly in cortical activity patterns can account for the vividness, richness of associations, and emotional intensity of memories recalled by stimuli.

Keywords: Carnot cycle; Criticality; Dissipative quantum model of brain; Ephapsis; Null spike; Phase cone

Contents

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1571-0645/$ – see front matter
http://dx.doi.org/10.1016/j.plrev.2013.01.001

1. Introduction

The aim of this review is to study the energy consumption of the brain in the framework of the dissipative many-body model [1–3] and the generalized Carnot cycle model [4]. We focus our attention on the expenditure of energy to facilitate the emergence of patterns and dissipation of so-called "dark energy" in knowledge retrieval. The general picture of the process by which brains construct knowledge from information and how the generalized Carnot cycle describes it is presented in the following subsections. In Section 2 we consider the interplay between the macroscopically observed high energy need of the brain and the many-body dynamics underlying the brain functional activity. Conclusions are presented in Section 3. In Appendix A the brain metabolic need of high energy density in conjunction with its dark energy dissipation is described. In Appendix B a brief summary of essential formal features of the dissipative many-body model is presented.

1.1. Knowledge, information and energy

Brains are thermodynamic systems that use chemical energy to construct knowledge from information [5,6]. The oxidative metabolism of glucose provides the energy, as measured by oxygen depletion and carbon dioxide production. The sensory receptors in the body and on the body surface provide the information by absorbing energy of various types impinging from the internal and external environments [7]. Each sensory receptor converts a stimulus, which is a local quantity of energy (light, heat, sound, concentration of a chemical), first to an ionic current (known as its receptor potential) and then to a train of pulses (action potentials, units, spikes) on its axon. Each pulse expresses a quantity of information by its location in time and space. The pulse train constitutes a point process. The sensory energy is weak [8], often a few molecules of scent, a few photons in a flash. Detection is facilitated by large arrays of equivalent receptors (10^7–10^8). The arrays form sheets on the body surfaces, which send bundles of axons into the brain. A stimulus is a configuration of energy in a pattern that is transmitted as information by the pulse intervals, frequencies and delivery sites by stages to the sensory cortices. A conditioned stimulus is a stimulus that has been paired with a painful or pleasurable unconditioned stimulus in reinforcement learning. It is in sensory cortex that the sensory information is organized at high density as knowledge and accumulated over the lifetime of an individual as memories.

In an act of recognition a conditioned stimulus triggers an operator, a Hebbian nerve cell assembly, that abstracts, amplifies and generalizes to the category of a stimulus [9]. The assembly forms by repeated samples of information in reinforcement learning according to the Hebb rule: neurons that fire together wire together. The conditioned stimulus ignites the entire assembly, so the output signals the category of the stimulus and not the stimulus *per se*. The associations learned under reinforcement convert the input of sensory information to the output of a fragment of knowledge. The assembly provides the bolus of energy required to generate a structured liquid-like phase (low entropy) out of a formless gas-like phase of random activity (high entropy), with a vanishing change in the free energy F, $dF = 0$. Such a process of phase transition is by spontaneous breaking of the symmetry of the gas-like phase [3], in the sense that the pre-stimulus phase is featureless in all directions, whereas the pattern of the post-stimulus phase cannot be rotated or translated into itself.

The conditioned stimulus ignites the entire assembly, so the output signals the category of the stimulus and not the stimulus *per se*. The assembly provides the bolus of energy required to initiate a phase transition from a formless gas-like phase of random activity to a structured liquid-like phase. The phase transition is by spontaneous breaking of the symmetry of the random phase [3].

The fragment of knowledge consists of the (low entropy) ordered pattern generated from broken symmetry. It is expressed in two interactive fields of neural activity, which spread over the entire sensory cortex. The dendrites of the neurons generate a high-energy-density field of electric current that synchronizes cortical activity in a narrow-band oscillation. The knowledge content is expressed in the spatial pattern of amplitude modulation (AM) [7,9,10]. In the biological model these AM patterns are generated by attractors that are structured by modified synapses constituting memories formed by learning in consolidation. The spread over the cortex is documented by a spatial pattern of the phase defined at the carrier frequency. The phase pattern has the form of a cone [10]; the phase gradient and velocity are determined by the carrier frequency and the conduction velocities of intracortical axons; the location and sign of the apex (phase lead or lag) vary randomly from each wave packet to the next regardless of contents. The inward phase