Binding Neuron

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INTRODUCTION

Although a neuron requires energy, its main function is to receive signals and to send them out – that is, to handle information. - F. Crick, The Astonishing Hypothesis, 1994

The brain ability to perform meaningful signal processing tasks related to perception, pattern recognition, reasoning is normally attributed to large-scale neuronal networks. The main signals involved in the instantaneous neural processing are neural impulses, and the units, which process impulses in a network, are individual neurons. We now put a question: In the context of higher brain functions, like perception, what is a meaningful task a neuron performs with the signals it receives? Another question: Does the inhibition exist for taming neuronal activity only, or it can be endowed with a more intelligent signal processing role? In this article, we propose an abstract concept of signal processing in a generic neuron, which is relevant to the features/events binding well known for large-scale neural circuits. Within this concept, action of inhibition obtains its natural signal processing meaning.

BACKGROUND

Low-Level Concepts of Signal Processing in a Neuron

The main part of any biological neuron is the excitable membrane. The membrane is able to generate electrical (neural) impulses, if proper stimulated, and to propagate those impulses over long distances without attenuation. The low-level concepts are concerned with electrochemical characteristics of initiating and propagating of the impulses. These concepts are expressed in the form of differential equations, which govern the time course of the transmembrane potential.

Hodgkin and Huxley Equations

If V denotes the displacement of the transmembrane potential of the excitable membrane from its resting state, then its time course is defined by the transmembrane currents as follows:

$$\frac{dV}{dt} = -\frac{1}{C_M}\sum_{k=1}^{n} I_k,\qquad(1)$$

where n is the number of different ionic currents considered, C_M is the capacity of the membrane unit surface and I_k, $k = 1,\dots,n,$ denote ionic currents through that surface. In the Hodgkin and Huxley (H-H) model, (Hodgkin & Huxley, 1952), three currents were considered, namely, the potassium, sodium and leakage current. These currents depend on the V by the following way:

$$
\begin{aligned}
I_K &= g_K n^4 (V - V_K),\\
I_{Na} &= g_{Na} m^3 h (V - V_{Na}),\\
I_l &= g_l (V - V_l),
\end{aligned}\qquad(2)
$$

where g_k, V_k, $k \in \{''K'', ''Na'', ''l''\}$ are time-independent. The so called gating parameters m, n, h depend on t in accordance to the following equations:

$$
\begin{aligned}
dn\,/\,dt &= \alpha_n(1-n) - \beta_n n,\\
dm\,/\,dt &= \alpha_m(1-m) - \beta_m m,\\
dh\,/\,dt &= \alpha_h(1-h) - \beta_h h.
\end{aligned}\qquad(3)
$$

Here parameters α_k, β_k, $k \in \{''h'', ''m'', ''n''\}$,depend on V in a nonlinear manner, see (Hodgkin & Huxley, 1952) for the exact expressions. The system (1)–(3) has resting state with $V = 0$. The temporal

dynamics is usually introduced into (1)–(3) through a choice of proper initial conditions with a nonzero V value. This corresponds to experimental manipulation known as the voltage clamp method. After the voltage clamp is released, the temporal dynamics of V can be observed either experimentally, or by solving (1)–(3) numerically.

The remarkable feature of the H-H set of equations is that if the initially clamped value of V corresponds to depolarization and is high enough, then the dynamics itself builds up further depolarization up to a definite value, V_{peak}, and then returns to its resting state. This transient process is known for real neurons as the action potential, or spike, and it constitutes the essence of the neural impulse, when propagates along the membrane of a neural fiber, (Hodgkin, 1971). Both for real neurons, and for the set of Equations (1)–(3) neither the time course of the action potential, nor its peak value does depend on the initially clamped value of V. Moreover, the time course of the action potential obtained by solving (1)–(3) is in perfect correspondence with that observed experimentally for the giant nerve fiber of squid (see Hodgkin & Huxley, 1952, Figs 13, 14).

The ideas of H-H equations received further development in several directions. First, additional ionic currents found in other neurons and the dynamical properties of corresponding ionic channels are added to the (2) and (3) (Huguenard & McCormick, 1992). Second, spatially distributed (compartmental) equations are considered in order to fit with morphology of real neurons (De Schutter & Bower, 1994). Third, for simplification of mathematical analysis, a reduced sets of equations were offered, which has lower dimension than (1)–(3), and still is suitable for generating spikes (FitzHugh, 1961).

Leaky Integrate and Fire Model

In the Leaky Integrate and Fire (LIF) neuron model (Stein, 1967; Knight, 1972), the membrane voltage time course is governed by the following differential equation:

$$\frac{dV}{dt} = \frac{1}{C_M} I(t) - \frac{1}{R_M C_M} V, \qquad (4)$$

where the first term corresponds to stimulating current due to input impulses and the second one – to exponential decay due to leakage. The model is additionally characterized with a threshold voltage, V_{th}. If V surpasses the V_{th}, then the neuron emits an impulse and V is reset to standard value, usually 0. The model has numerous modifications (Burkitt, 2006). The LIF model appeared to be quite useful for studying statistics of activity in individual neurons and neuronal populations.

The low level models were designed for quantitative description of membrane voltage and currents interplay. Any low level model retains a possibility to fire an output impulse (spike). The decision to fire or not is made based on the membrane voltage time course. At the same time, the output impulses emitted from a neuron are identical, bearing the only label – the emitting moment. The same should be expected about the input impulses for a neuron embedded in a neuronal network[1]. If so, then it would be natural to formulate the firing criterion in terms of arriving moments of the input impulses.

DIRECT REDUCTION TO LOW-LEVEL CONCEPTS IS UNFEASIBLE

The understanding of mechanisms of higher brain functions expects a continuous reduction from higher activities to lower ones, eventually, to activities in individual neurons, expressed in terms of membrane potentials and ionic currents. While this approach is correct scientifically and desirable for applications, the complete range of the reduction is unavailable to a single researcher due to human brain limited capacity. An attempt to describe a task solving within a brain in terms of membrane potentials and ionic currents would be similarly hopeless as to describe in terms of Kirchhoff's point and loop equations a program execution in a computer. In the computer circuits design, many abstractions, like NAND-gate, NOR-gate and so on, are used. The gates can be constructed as electrical or optical cells, but the hardware description language (see Shahdad, Lipsett, Marschner, Sheehan, & Cohen, 1985) deals only with abstract logical essence of the gate concept while concrete physical mechanisms employed are studied within another branch of science.

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