Signals in nerves from the philosophical viewpoint

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Abstract

The signals in nerve include electrical, mechanical and thermal components and are characterized by the complexity of processes. The modelling of these signals is analyzed from the viewpoint of DeLanda who has demonstrated the possibility to expose the philosophical theories of Deleuze by using the notions from nonlinear dynamics. It is demonstrated that the mathematical modelling of processes in nerves by authors of this paper follows the general ideas of multiplicity and causal interactions described by DeLanda.

Keywords: Nerve signals, interdisciplinarity, modelling, complexity, epistemological analysis

1. Introduction

The propagation of signals in nerves is a fascinating problem which is related to cognitive processes and processing of neural information. Much is known about signal propagation in nerves from the physical and physiological viewpoint. The experimental studies and theoretical predictions over the last two centuries have cast light on main mechanisms responsible for signal formation and propagation. Besides the physical description, this complex process or the physics of thought should also be analyzed from the philosophical viewpoint. Noble [1] has stressed the need "to unravel the complexity of biological processes" and suggested modelling in an integrative way. This is important for understanding the emergent properties in biological systems and the interaction processes responsible for them [2]. The nervous system is a complex structure and as Koch and Laurent [3] stress one should account for "the highly nonlinear, nonstationary, and adaptive nature of the neuronal elements" which needs to understand the context in which the system operates. Much attention has been paid to physical complex systems which need using mathematical description developed in nonlinear dynamics [4–6]. The overviews on modelling the signal propagation in nerves [7–11] demonstrate the complexity of the process. The keywords of this process like nonlinearity, coupling, emergent structures, etc are characteristic for many phenomena which have caused the analysis from a wider perspective than just nonlinear dynamics or system biology. Many philosophers have paid attention to complex systems like Morin [12] and Deleuze and Guattari [13] if to mention just a few. From the viewpoint of physical systems, the studies of DeLanda [14] are important because he has explained the philosophical ideas of Deleuze in terms of nonlinear dynamics.

In what follows, the ideas of DeLanda and Deleuze are used to characterize the modelling of signals in nerves proposed by Engelbrecht, Tamm and Peets (see [11]). It is demonstrated that such modelling corresponds to general philosophical ideas. In Section 2, the ideas of modelling [11] are briefly explained. Section 3 presents the ideas of DeLanda [14] based on the philosophical notions of Deleuze but reconstructing them within the framework of mathematical terminology. Section 4 deals with the modelling of signals in nerves by comparing the ideas with the philosophical framework. Finally, in Section 5 some conclusions are drawn.

2. Mathematical modelling of signal components in nerves

Here we follow the ideas of modelling proposed by Engelbrecht, Tamm and Peets in their recent publications [15–21], see also Peets and Tamm [22]. The modelling is based on the careful analysis of mechanisms of electromechanophysiological interactions (see summary by Engelbrecht et al., [21]). An overview of the principles of modelling is presented by Engelbrecht et al., [11]. This model follows the **scheme**:

(i) Derive time-dependent models (equations) for all the effects which seem to be significant for the whole process based on physical laws;
(ii) Propose coupling mechanisms between the effects;
(iii) Solve the coupled system of equations;
(iv) Validate the results by comparing them with experiments.

As usual, one should start from **assumptions**:

(i) electrical signals are the carriers of information [23] and trigger all the other processes (which is shortly called Hodgkin-Huxley paradigm);
(ii) the axoplasm in a nerve fibre can be modelled as fluid where a pressure wave is generated due to electrical signal;
(iii) the biomembrane can deform (stretch, bending) under the mechanical impact [24];
(iv) the channels in biomembranes can be opened and closed under the influence of electrical signals as well as of the mechanical input [25];
(v) there is strong experimental evidence on electrical or chemical transmittance of signals from one neuron to another [26].

Next, the **hypotheses** are introduced [17, 19]:

(i) all mechanical waves in axoplasm and surrounding biomembrane together with the heat production are generated due to changes in electrical signals (AP or ion currents) that dictate the functional shape of coupling forces;
(ii) the formalism of internal variables can be used for describing the exo- and endothermic processes of heat production;
(iii) the changes in the pressure wave may also influence the waves in a biomembrane.

Based on these assumptions and hypotheses, essential **remarks** are the following:

(i) the changes of variables mean mathematically either space or time derivatives;
(ii) the pulse-type profiles of electrical signals mean that the derivatives have a bi-polar shape which is energetically balanced.
(iii) the coupling is assumed due to forces in corresponding governing equations;
(iv) the functional shapes of coupling forces are proposed in the form of first-order polynomials of gradients or time derivatives of variables [15, 16].

As a result of modelling, it is possible to simulate an **ensemble** of waves in the axon. This ensemble has the following components (notations correspond to the dimensionless case):

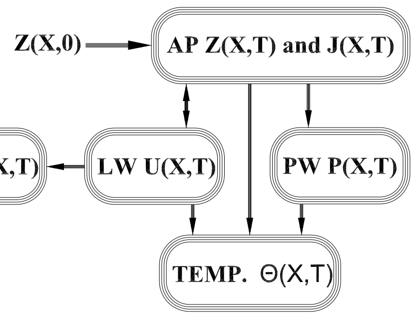

Figure 1: The components and interactions of the mathematical model. The ensemble starts with an initial excitation $Z(X,T)$ at $T=0$ above a threshold value leading to an emergence of an electrical signal AP. Then the other members of the ensemble emerge over a certain time caused by coupling forces. Here X, T denote dimensionless space and time, respectively.

(i) the action potential AP which has an amplitude Z and the ion currents. In case of the Hodgkin-Huxley (HH) model, these ion currents are J_K, J_{Na} and J_L, in case of the FitzHugh-Nagumo (FHN) model just one ion current J (here the ion currents for the HH model denote potassium, sodium and leakage currents, respectively).

(ii) the longitudinal wave LW in the biomembrane with an amplitude U;

(iii) the transverse displacement TW in the biomembrane with an amplitude W;

(iv) the pressure wave PW in the axoplasm with an amplitude P;

(v) the temperature change Θ.

The ensemble is composed of primary and secondary components: the primary components (AP, LW, PW) are characterized by finite velocities while the secondary components (TW, Θ) have no characteristic velocities.

This is the backbone of modelling with details explained in references above. The final mathematical model is a system of coupled differential equations [18, 19]. The system in the equilibrium state is excited by an electrical signal above a certain threshold which generates the AP and then all the other components of the ensemble are generated which is qualitatively similar to experimental data (cf analysis by Engelbrecht et al., [16, 19]). The backbone of modelling is based on consistent physical laws but is open for further modifications. The structure of the mathematical model and interactions between its components are depicted in Fig. 1.

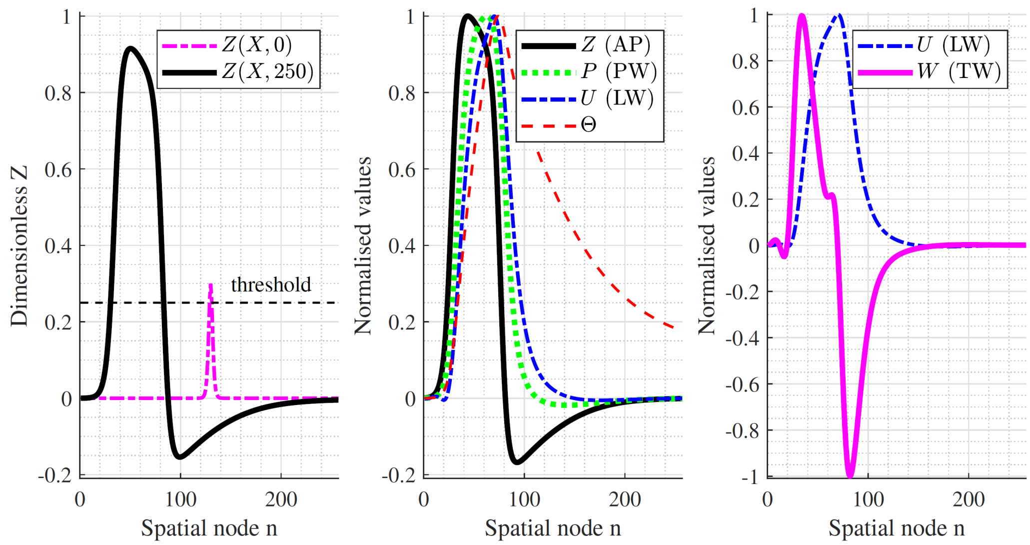

Figure 2: A typical nerve pulse ensemble formation and propagation. Left – (a) generation of the AP (solid line, at $T = 250$) from an initial input (dash-dot line, at $T = 0$). At $T = 250$ a typical shape of the AP has been formed from the narrow 'spark' type initial condition; Middle – (b) the components of AP, PW, LW and Θ; Right – (c) the components of LW and TW. The initial condition in the middle of the spatial period ($n = 2048$) forms left and right propagating AP, which, in turn, generates all the other signals through coupling forces. Left propagating waveprofiles are shown in a moving frame of reference ($n = 256$) at $T = 250$ for (a) and at $T = 800$ for (b) and (c). Here n is a computational node in a dimensionless space X and T denotes dimensionless time. For mathematical details and values of model parameters see [21].

For numerical simulations, the system of governing equations is solved by using the pseudospectral method [22]. Leaving aside the structure of this system with its coefficients, a typical ensemble in dimensionless variables is shown in Fig. 2. The input (Fig. 2a) is above the threshold and it takes a certain time before a typical AP is formed. The ensemble (Fig. 2b) corresponds qualitatively to the experimental results as well as the shape of the TW (Fig. 2c).

3. Modelling viewed from the philosophical viewpoint

The following analysis is based first on the DeLanda [14] analysis of ideas of Deleuze and Guattari [13] by a conceptual explanation of mathematics involved and second, on the analysis of assemblages by DeLanda [27]. DeLanda [14] explains how the ideas of multiplicity developed by Deleuze can be described within the theory of differentiable manifolds which are widely used in nonlinear dynamics. As stressed by Holdsworth [28], DeLanda "recovers for mathematical practice a capacity to clarify the meaning of events as they arise within a synthetic process of becoming interdisciplinary". The focus of Deleuze's studies is on dynamical processes and in this context, one has to analyze in the system being modelled: (1) a range of behaviour, fluctuation, patterns and thresholds; (2) in the dynamical model: phase space, trajectory, attractors and bifurcations; (3) in the mathematics used to construct the model: manifold, function and singularity [29]. This is done by DeLanda [14] in detail. However, one should add to modelling the physical processes that the basic physical laws must always be checked [11, 18]. This is emphasized by DeLanda [14] by stressing the need to understand the basics. He assumes a minimum of objective knowledge to get the process going and then accounting for the rest. This corresponds to the well-known principle of Occam's razor - entities are not to be multiplied without necessity. Such an attitude is also supported by Albert Einstein [30]: "... the supreme goal of all theory is to make irreducible basic elements as simple and as few as possible ...". Without going into details, let us list essential ideas of DeLanda [14] which will be useful in the analysis of signals in nerves.

- Interdisciplinarity is needed for understanding the complex processes.
- Complex processes are characterized by multiplicity which is the activator for changes in the system.
- Multiplicity is characterized by differences which are productive and cause interactions.
- One should distinguish between intensive and extensive properties of systems; intensive properties like pressure, temperature, density, etc cannot be divided, extensive properties like length, area, volume, amount of energy can be divided into parts, intensive properties have critical thresholds, differences (gradients) in intensity store potential energy.
- The whole emerges from parts by causal interactions.
- The changes (gradients) are characterized by velocities (or differential relations).
- The causality for processes is related to multiplicities.

- Non-equilibrium (intensive by DeLanda) states demonstrate explicitly the potential of nonlinearities which do not cause essential differences in equilibrium states or close to them.

- One should distinguish between intrinsic (belonging to the system) and extrinsic (originating from outside) conditions for a system.

- Emergence means a process where novel properties and capacities emerge from causal interaction.

- One should understand the inertiality of a system and the role of thresholds and triggers in dynamical processes.

- Every physical process means also the transfer of information.

Also, DeLanda argues about the notion 'assemblage' [27] which is also introduced by Deleuze. The assemblage means in English a gathering of things together into unities which are actually different by the notion of 'agencement' in French like Deleuze has proposed. A unity in the assemblage is defined "by the intrinsic relations that various parts have to one another in a whole" [31] while Deleuze [32] accounts for the external relations by using 'agencement' and in this way includes also the process of the formation into the notion.

4. How the modelling of signals in nerves corresponds to philosophical ideas

First, it must be stressed that the modelling of signals in nerves briefly described in Section 2, is based on interdisciplinary considerations [20]. Indeed, the knowledge from physics and continuum mechanics is used for describing the physiological effects within the framework of mathematics. The laws of physics (balance of momentum, the Fourier's law) are basic although they are modified to grasp the physiological effects. From the epistemological viewpoint, the basic laws constitute propositional knowledge (knowing that). The ensemble of waves emerges as a result of interactions of intensive properties of the system and the coupling forces are related to changes of field variables (time or space derivatives) with the corresponding mathematical description. To model temperature changes the role of possible chemical reactions (exo- and endothermic processes) is described by the concept of internal variables widely used in continuum mechanics. The main role in signal formation is related to intrinsic properties of structural elements of axons but is also dependent on the extrinsic properties like the temperature of the environment or the ion concentration of the extracellular fluid. The signal formation is influenced by the multiplicity of processes - for example, the temperature effects are caused by several mechanisms. The system is characterized by a threshold of the trigger - the initial condition for generating the AP should be above the threshold. The mechanical components of the ensemble depend on inertia as it should be for wave processes. This dependence has a direct consequence for the width of the LW in the biomembrane.

In terms of DeLanda, the ensemble of waves can be called the 'assemblage'. However, as far as the notion of 'ensemble' does not describe the process of formation, then in order to associate two notions, one could use 'dynamical ensemble' which stresses possible changes, i.e., not only the propagation but also the process of formation. This way or another, the ensemble of waves in nerves is a result of the causal interaction resulting in a complex. This complex is a carrier of information and serves as a basic element for neural networks. Figure 1 demonstrates also the importance of using the diagrams noted by DeLanda [27] for explaining the causal relations in his philosophical analysis.

The multiplicity of effects characteristic to signals in nerves analysed above is limited to the propagation effects. The modification of intrinsic and extrinsic properties could certainly improve the predictive power of the model. For example, the coupling (activation) forces may need specifying by the more refined description of lipids in the biomembrane or of filaments in the axoplasm. The molecular effects related to ion movement and the influence of membrane proteins might influence the emergence of an ensemble. The influence of the temperature of the environment as an extrinsic property can be accounted for by the coefficients of the governing system.

The propagation of signals in nerves is a part of phenomena in the brain which are much more complicated. Goriely et al., [33] have shown how the interdisciplinarity can help to understand the multiplicity of processes needed for the analysis of the extremely complex function of the brain at many scales (at molecular, cellular, and tissue levels).

5. Final remarks

In Section 4, it is demonstrated that the descriptions presented in Sections 2 and 3 follow similar lines. Historically the analyses and the explanations have used different terminology but in essence, the ideas are similar. The mathematical model, described above, is based on the analysis of physical mechanisms [21]. Kaplan and Craver [35] have formed a model-to-mechanism-mapping requirement that says: “In successful explanatory models in cognitive and systems neuroscience (a) the materials in the model correspond to components, activities, properties, and organisational features of the target mechanism that produces; maintains, or underlines the phenomenon, and (b) the (perhaps mathematical) dependencies posited among these variables in the model correspond to the (perhaps quantifiable) causal relations among the components of the target mechanism”. This is exactly the ideology followed in our modelling. For nerve signals, models of single effects are brought together by coupling forces which depend on changes of intensive field variables. As a result, an ensemble is formed which is a carrier of information. All the keywords of Section 3 on philosophical ideas: interdisciplinarity, basic laws, multiplicity, changes of intensive variables, nonlinearities, causality are used in the mathematical modelling of signals in nerves. Certainly, it is not just the collection of keywords that correspond to the philosophy of DeLanda, it is the whole construction of the modelling following the idea of the assemblage which is the emergence of a whole from parts due to interactions. In the nutshell, as stressed by Delanda [34], intensive differences are productive - this is actually the essence of the philosophy behind modelling of signals in nerves.

Such philosophy is characteristic to the modelling of nervous systems from the viewpoint of complexity including nonlinear and nonstationary effects [3]. The role of interactions in systems biology is stressed in many studies [1, 36] and reflects also the philosophical ideas stressed briefly above. Finally, it must be stressed that the discussion on explanatory and modelling strategies in systems biology involves also the question of whether these strategies are mechanistic [37]. Clearly, the investigations of philosophical accounts in systems biology serve a better understanding. In principle, we agree with Driessen [38] who says that “philosophy is a good school for developing the intuitive capacity of scientist”.

Acknowledgments

This research was supported by the Estonian Research Council (IUT 33-24).

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