Neural activity pattern systems

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Abstract

Understanding how neural systems work needs appropriate models. Here we propose a model that describes neural systems in terms of abstract communication systems. We indicate how to apply the proposed framework to the analysis of real neural systems.

Key words: communication system, neural network model, neural systems, pattern language

1 Introduction

To understand how biological neural systems work it is crucial to select the right models providing an appropriate level of abstraction. Several models were proposed in the past decades. Some of these emphasize the role of single neurons as fully functional computational building blocks (e.g., neurons as basis functions) [5]. Others focus on the role of neural populations and averaging computations performed by such populations [4]. Another group highlights the nonlinear dynamics of neural activity patterns and suggest that neural computations may be performed by switching between attractors defined in the space of activity patterns [3]. More recently it was suggested that pattern languages [8],[2] can be used to interpret the activity patterns recorded from neural systems [2], and models were proposed to show how computations with such activity patterns can be performed (e.g.,[1]).

This paper follows the track of interpretation of neural systems in terms of pattern languages. We propose a formalized description of neural systems as activity pattern systems and outline how to apply this interpretational context to the case of the stomatogastric ganglion (STG) of crabs.

2 Conceptual foundations

We introduce in this section a conceptual framework for the description of communication systems [6]. Communication units are entities which produce communication behaviours. We ignore the internal structure of communication units. Communication units may perceive communication behaviours of other units and in response may generate communication behaviours. Communication is the process of producing a communication behaviour by a communication unit followed by the perception of this behaviour by another communication unit.

Communications are produced according to probabilistic rules depending on earlier communications; these rules are called continuation rules. The set of earlier communications on which depends the production of a new communication is called the referencing set of the new communication. A communication system is characterized by a set of such continuation rules. Those communications are part of the communication systems, which follow the rules characterising the communication system. A communication system consists of a dense referencing cluster of communications. Communication units are not part of the communication system.

The environment of a communication system is made of communications that are not part of the system. The environment poses constraints on the communication system by imposing the likelihood of producing communication behaviours. Communication systems compete for communications to maintain themselves. Communication systems that fit better the environmental constraints may out compete other communication systems that fit less well to the environmental constraints.

3 Neural communication systems

3.1 Behaviours, communications, environment

We consider neurons as communication units and spike sequence patterns of neurons as communication behaviours in neural systems. The communication behaviours that we consider are slow spiking, fast spike burst, and other similar spike sequence patterns. We will denote neurons as X_k and spike sequence patterns as x_j. The fact that neuron produced the spike pattern x_j at time $t-\tau$ is denoted as $(X_k, x_j)_{-\tau}$, where the current time is t.

The communications composing the neural communication system are spike sequence patterns produced by neurons and perceived by the same or other neurons. These communications depend on earlier communications between neurons. This dependence is formalized as rules expressing probabilities of producing spike sequence patterns x_j by a neuron X_k depending on spike sequence patterns produced by the same or other neurons that are connected to the neuron X_k. Formally we write

$$P^i_{X_k}(x_j|R^i(X_k, x_j)) \tag{1}$$

where $R^i(X_k, x_j)$ is the referencing set of the rule. The same spike sequence pattern x_j may be produced by several rules with different referencing sets. In general a referencing set is of the form

$$R^i(X_k, x_j) = \{(X_u, x_v)|X_u \textit{ is connected to } X_k, \textit{ and } \tau > 0\} \tag{2}$$

Not all neurons X_u sending connections to X_k have to be listed in the referencing set of all rules applying to X_k, and only a finite selection of τ values appear in any referencing set. An inter-referencing cluster of neural communications that follow a set of continuation rules constitutes a neural communication system. A neuron may produce communication behaviours that are part of different neural communication systems.

The environment of neural communications systems is composed of other communications, including communications at the level of components of neurons. The environment imposes constraints on the neural communications system in terms of imposing the likelihood of communication behaviours, i.e., of spike sequence patterns. We write these constraints as

$$Q(x_j) \tag{3}$$

the probabilities of occurrence of spike sequence patterns x_j. These probabilities may change in effect of neuromodulators. A neural communication system can be maintained in such environment if an appropriate distribution of spike sequence patterns is produced by application of its rules.

3.2 Communication systems

Considering the above descriptions we can write the equations determining the neural communication systems that can exist under a set of environmental constraints.

The following notations are used:

$$a_{kij} = P^i_{X_k}(x_j|R^i(X_k, x_j)) \tag{4}$$

$$q_j = Q(x_j) \tag{5}$$

The probability of producing spike sequence pattern by neuron is

$$p_{kj} = P(X_k, x_j) = \frac{\sum_{i=1}^{r_j} P^i_{X_k}(x_j|R^i(X_k, x_j)) \cdot P^i(R^i(X_k, x_j))}{\sum_{i=1}^{r_j} P^i(R^i(X_k, x_j))} \tag{6}$$

where r_j is the number of rules for neuron X_k that produce spike sequence pattern x_j. The probability of producing spike sequence pattern x_j by the system is

$$P(x_j) = \frac{1}{N} \sum_{k=1}^{N} P(X_k, x_j) \tag{7}$$

where N is the number of neurons in the system. For simplicity, we suppose the independence of the referenced communication. In this case the likelihood of satisfactory referencing sets is given by

$$P^i(R^i(X_k, x_j)) = \prod_{(X_u, x_v) \in R^i(X_k, x_j)} P(X_u, x_v) \tag{8}$$

The equations determining the possible neural communication systems are

$$\begin{cases} p_{kj} = \dfrac{\sum_{i=1}^{r_j} a_{kij} \prod_{(X_u,x_v)\in R^i(X_k,x_j)} P(X_u,x_v)}{\sum_{i=1}^{r_j} \prod_{(X_u,x_v)\in R^i(X_k,x_j)} P(X_u,x_v)};\ k = 1, N;\ j = 1, M \\ q_j = \frac{1}{N} \sum_{k=1}^{N} p_{kj};\ j = 1, M \end{cases} \tag{9}$$

with the constraints that $p_{kj} \in [0, 1]$. The parameters of the above system are $a_{kij} \in (0, 1)$ and $q_j \in (0, 1)$. A neural communication system is characterised by a subset of a_{kij} values for which the above system has at least one solution in terms of p_{kj}-s, with the q_j-s being given by the environmental constraints. Not all subsets of values a_{kij} allow a solution for the equation system (9).

Setting the environmental constraints (i.e., q_j-s) selects the neural communication systems that are compatible with the constraints. New system behaviours are learned by selecting a new subset of continuation rules (i.e., a_{kij}-s) that fit to new constraints imposed by the environment. The dynamics of changing the active neural communication system is driven by the difference between the actual distribution of x_j-s and the distribution of them imposed by the environmental constraints. The effect of the environmental constraints is the alteration of the output of the continuation rules. The difference between the actual and environmental constraints implied distribution imposes a prior distribution over the communication behaviours x_j

$$\widehat{q}_j = \widehat{Q}(x_j) \propto Q(x_j) - P(x_j) \tag{10}$$

The effective likelihood of producing spiking sequence pattern x_j by neuron X_k is given by

$$\widehat{p}_{kj} = \frac{p_{kj} \cdot \widehat{q}_j}{\sum_{j=1}^{M} p_{kj} \cdot \widehat{q}_j}$$

By producing spike sequence patterns forced by the environment, but which do not fit into the existing neural communication system, the communications move toward a new neural communication system. In effect a new neural communication system emerges from the communications between the neurons, such that the communications following the rules of the new system produce a communications behaviour distribution that fits the environmental constraints.

3.3 Interpreting real neural systems

The crab stomatogastric ganglion (STG) is a simple and well-known neural system [7]. The connectivity structure of the ganglion and many details about the transmitters and neuromodulators involved in the activity of the STG are well known. It is still not very clear how this relatively small system (i.e., $30 - 40$ neurons) composes several functional networks (e.g, gastric network) and produces a large variety of output activity patterns.

The above described framework for interpreting activities in neural systems provides a new way to understand how the STG works. We see the functional networks as neural communication systems that dominate communications between a subset of the STG neurons under certain environmental constraints. The environmental constraints in the STG are provided by the neuromodulators that switch the STG between supporting one or another functional network. The wide variety of activity and output patterns of the STG can be interpreted as the result of a multitude of continuation rules for spike sequence patterns. Testing our predictions about the applicability of the proposed interpretational framework should be possible by analysing simultaneous activity patterns of many neurons of the STG. Such analysis should reveal the active continuation rules. Measuring the amount of neuromodulators and higher inputs should allow establishing the effective environmental constraints that select between the continuation rules to form the functional networks within the STG.

4 Conclusions

Appropriate models and interpretational frameworks are needed to understand how neural systems work. Here we propose a new such framework that follows the works on pattern languages applied in the context of neural systems. According to our proposal neural systems provide the substrate for several neural communication systems characterized by a set of continuation rules which determine which spike sequence patterns follow other spike sequence patterns. In the proposed context the environmental constraints select the active subset of such rules which produce spiking activity compatible with the constraints.

References

[1] P. Andras, Pattern languages: A new paradigm for neurocomputation, To appear in Neurocomputing (2004).

[2] P. Andras, A Model for Emergent Complex Order in Small Neural Networks. Journal of Integrative Neuroscience 2 (2003) 55-70.

[3] W.J. Freeman, Role of chaotic dynamics in neural plasticity, Progress in Brain Research 102 (1994) 319-333.

[4] A.P. Georgopoulos, A.B. Schwartz, and R.E.Kettber, Neuronal population coding of movement direction. Science, 233 (1986) 1416-1419.

[5] S. Haykin, Neural Networks. A Comprehensive Foundation (Macmillan Publishers, Englewood Cliffs, NJ, 1994).

[6] N. Luhmann, Social Systems. (Stanford University Press, San Francisco, 1996).

[7] M.P. Nusbaum and M.P. Beenhakker, A small-systems approach to motor pattern generation, Nature, 417 (2002) 343-350.

[8] S. Wolfram, A New Kind of Science (Wolfram Media, Champaign, IL, 2002).