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MODELING THE IMPULSE TRANSMISSION THROUGH A SYSTEM OF TWO SYNAPSES

A model describing the process of nerve signal transmission through a system consisting of two interacting synapses has been proposed. The model is based on nonlinear differential equations that describe the activation of receptors on the postsynaptic membranes of two synaptic clefts. The interaction between the synapses is implemented in such a way that the activation of receptors on the first postsynaptic membrane determines the intensity of mediator injection into the second synapse. The peculiarities of the stationary state of this system have been studied, and the stability of this state has been shown. The influence of the intensity of mediator injection into the first synapse of the system on the concentration of activated receptors in the second synapse has also been analyzed. It has been demonstrated that the reliability of the entire system is not violated at a qualitative level, and the character of the receptor activation process on the postsynaptic membrane of the second synapse remains stable with respect to variations in the input signal.

Keywords: impulse, synapse, mediator, membrane, receptor, activation.

If the world were perfect, it wouldn't be.
Yogi BERRA

1. Introduction

The study of synaptic signal transmission has a long and interesting history [1–5] with its own notable highlights [6–10]. A significant number of studies have been devoted to this problem. Moreover, since the problem is complicated and diverse, the approaches to its solution are also diverse. A special place among them is occupied by studies based on biophysical models. The basis of the latter was laid in work [11] and then expanded and detailed in a series of works [12–19]. In the context of these studies, a number of related works on the diffusion processes in synapses [20–22], the pool organization of the presynaptic region [23–32], and the influence of feedback on the stability and reliability of neural signal transmission channels [33–38] can be additionally marked out. Another important segment of research that is not directly related to the functioning of synapses, but actually plays an important role in the formalization and determination of the mechanisms of synaptic information transmission, concerns the study of spatially confined fluid systems in the vicinity of the critical state and the specificity of phase transitions and diffusion phenomena in such systems, especially in the presence of biochemical reactions (see, for example, works [39–44] and the references therein). The matter is that the problem, which was first formulated in work [11], is interdisciplinary by its nature, so its solution implies the involvement of methodological and categorical apparatus from both the field of neuroscience and the field of the physics of critical phenomena and phase transitions, being based on the isomorphism of various phenomena and models in the relevant fields [11–13].

In this work, a model describing the process of nerve impulse transmission through a system of two synapses connected in series is proposed. The model is a mathematical abstraction that takes into consideration the following circumstances (see, for example, works [11–13]).

- A signal from the input neuron to the output one is transmitted through a contact called a synapse. A synapse is a gap between the presynaptic and postsynaptic membranes.

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• When transmitting a signal that arrives at the presynaptic membrane of the input neuron, a special substance called the mediator is injected from the presynaptic membrane into the synapse. The mediator diffuses to the postsynaptic membrane of the output neuron and activates specific receptors on it.

• The activation of receptors on the postsynaptic membrane leads to the generation of an action potential, which is further propagated by the output neuron.

• The transmitted signal, when reaching the presynaptic membrane of its neuron, triggers the sequence of events described above, and so on.

An important circumstance is also the existence of a mathematical model to describe the transmission of a signal through a synapse [11–19], which explains the main stages of the process quite well. However, in its original interpretation, it does not describe the transmission of a nerve signal through a sequence of neurons. From the viewpoint of system physiology, here we have a complicated process associated with the generation of an impulse due to the activation of receptors on the postsynaptic membrane, and the injection of a mediator into the synapse due to the arrival of the impulse. On the other hand, the general picture is clear, and can be reduced to the following: the activation of the postsynaptic membrane of a neuron ultimately results in the injection of mediator into the synapse at another contact, which stimulates the activation of the postsynaptic membrane of the next neuron in the chain. At the phenomenological level, it can be argued that the activation of the postsynaptic membrane of the first neuron is the cause of the activation of the postsynaptic membrane of the second neuron. The only question is how can this effect be described mathematically? In fact, the issue concerns the effect of one synapse on another.

The model proposed below makes allowance for the above-mentioned interaction by introducing a special term into the model differential equation that describes the activation of the postsynaptic membrane of the second neuron. This term, in turn, depends on the activation state of the postsynaptic membrane of the first neuron.

It should be noted at once that although the model is somewhat simplified and takes into account the interaction of synapses at a rather general level, it has not only a theoretical, but also certain practical value due to its application in artificial intelligence systems consisting of elements that are close by their parameters to real neurophysiological systems.

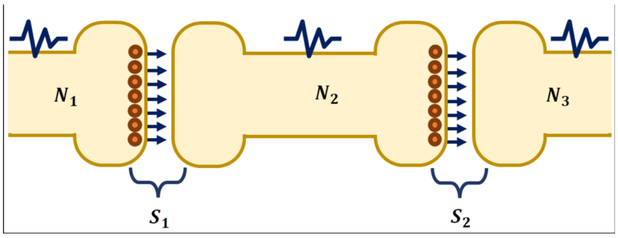

Fig. 1. The system under study: N_1 is the first (input) neuron, N_2 is the second (central) neuron, N_3 is the third (output) neuron, S_1 is the first synapse, S_2 is the second synapse

2. Basic Model

Hence, let us consider a system consisting of two synapses that actually connect three neurons: the first (input) neuron N_1, the second (central) neuron N_2, and the third (output) neuron N_3, as shown in Fig. 1. These neurons are connected by the first (S_1) and second (S_2) synapses. In essence, we have two synapses in the system; each of them is confined by a presynaptic and a postsynaptic membrane. The injection of mediator occurs through the presynaptic membrane, and the receptors are located on the postsynaptic membrane, where they are activated as a result of interaction with the mediator.

As concerning a separate synapse, according to works [11–19], the process of receptor activation on the postsynaptic membrane can be described using the system of two equations,

$$\frac{dr}{dt} = k_1(R_0 - r)m - k_2 r, \tag{1}$$

$$\frac{dm}{dt} = f(t) - k_1(R_0 - r)m, \tag{2}$$

where $r(t)$ denotes the concentration of activated receptors on the postsynaptic membrane, $m(t)$ is the concentration of mediator in the synapse, R_0 is the total concentration of receptors (both activated and non-activated) on the postsynaptic membrane, the function $f(t)$ describes the intensity of mediator injection into the synaptic cleft, and k_1 and k_2 are the phenomenological parameters of the model. The first term on the right-hand side of Eq. (1) describes the increase in the concentration of activated receptors due to the transition of non-activated receptors into the activated state. By assumption, the intensity of this process is proportional to the concentration of non-activated receptors, which is equal to $R_0 - r$, and the mediator concentration in the cleft, m. The same term, but with the opposite sign, in Eq. (2) describes the process of mediator reduction in the synapse due to the formation of mediator-receptor complexes upon the receptor activation. Here, it is assumed that for each activated receptor, there is a mediator molecule that interacts with the receptor and transits into the receptor-bound state. The second term in Eq. (1) describes the process of decrease in the concentration of activated receptors owing to the transition of receptors from the activated state into the non-activated one. The intensity of this process is assumed to be proportional to the concentration of activated receptors, r.

As was noted above, this model is extended to describe the functioning of a system of two interacting synapses. To formalize the problem, we will use the subscript 1 for the first synapse and the index 2 for the second synapse (see Fig. 1). Then, the following system of equations is obtained:

$$\frac{dr_1}{dt} = k_1(R_0 - r_1)m_1 - k_2 r_1, \tag{3}$$

$$\frac{dm_1}{dt} = f_1(t) - k_1(R_0 - r_1)m_1, \tag{4}$$

$$\frac{dr_2}{dt} = k_1(R_0 - r_2)m_2 - k_2 r_2, \tag{5}$$

$$\frac{dm_2}{dt} = f_2(t) - k_1(R_0 - r_2)m_2, \tag{6}$$

where $r_1(t)$ and $r_2(t)$ stand for the concentrations of activated receptors on the postsynaptic membranes of the first and second, respectively, synapses; $m_1(t)$ and $m_2(t)$ are the mediator concentrations in the first and second, synapses, respectively; and the functions $f_1(t)$ and $f_2(t)$ determine the intensity of mediator injection into the first and second, respectively, synapses.

However, in this presentation, system (3)–(6) is too general. Let us specify it by setting

$$f_1(t) = 0, \tag{7}$$

$$f_2(t) = k_3 r_1(t). \tag{8}$$

Relationship (7) means that the mediator is not injected into the first synapse, and relationship (8) describes the interaction of the synapses. This interaction, according to our assumption, consists in that the intensity of mediator injection into the second synapse is proportional to the concentration of activated receptors on the postsynaptic membrane of the first synapse.

For practical use, the model should be made dimensionless. For this purpose, let us put $r_i = R_0 x_i$, $m_i = R_0 y_i$, $i = 1, 2$, and also scale the time by setting $t = \frac{\tau}{k_1 R_0}$. Then, we get the following system of equations:

$$\frac{dx_1}{d\tau} = (1 - x_1)y_1 - \alpha x_1, \tag{9}$$

$$\frac{dy_1}{d\tau} = -(1 - x_1)y_1, \tag{10}$$

$$\frac{dx_2}{d\tau} = (1 - x_2)y_2 - \alpha x_2, \tag{11}$$

$$\frac{dy_2}{d\tau} = \beta x_1(1 - x_2)y_2, \tag{12}$$

where $\alpha = \frac{k_2}{k_1 R_0}$ and $\beta = \frac{k_3}{k_1 R_0}$. This system is nonlinear and, in the general case, can be solved only numerically. However, besides the solutions themselves, the issue of the stability of system (9)–(12) is of interest.

3. System Stability

The system of equations (9)–(12) has an obvious zero stationary solution $x_1 = y_1 = x_2 = y_2 \equiv 0$. If we use the notation $\mathbf{z} = (x_1, y_1, x_2, y_2)^T$, then, in the linear approximation, we easily obtain

$$\frac{d\mathbf{z}}{d\tau} = \hat{A}\mathbf{z}, \tag{13}$$

where the matrix

$$\hat{A} = \begin{pmatrix} -\alpha & 1 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -\alpha & 1 \\ \beta & 0 & 0 & -1 \end{pmatrix}. \tag{14}$$

The eigenvalues of the matrix $\hat{A}$ are $\lambda_1 = -1$ and $\lambda_2 = -\alpha$, each of multiplicity 2. As a result, the general solution of Eq. (13) is a linear combination of first-degree polynomials in τ and multiplied by exponential functions with the exponents $-\tau$ and $-\alpha\tau$. This means that the zero stationary solution is stable. From a practical point of view, this result leads to an important conclusion, since this solution means that no random signal will be generated in the system, and, in this sense, this system represents a reliable channel of signal transmission.

Another important point regarding system (13) is related to the fact that its solution determines the dynamics of the parameters $x_{1,2}$ and $y_{1,2}$ in the linear approximation, which is obviously valid if the deviations of the concentrations of the activated receptors and the mediator from zero are small. If we assume that the system leaves the equilibrium state as a result of the initial random injection of the mediator into the first synapse, then the solution of system (13) looks like

$$x_1(t) = \frac{m_0}{\alpha - 1}(\exp(-\tau) - \exp(-\alpha\tau)), \quad (15)$$

$$y_1(t) = m_0 \exp(-\tau), \quad (16)$$

$$x_2(t) = \frac{m_0\beta(\alpha\tau - \tau - 2)}{(\alpha-1)^3}\exp(-\tau) + + \frac{m_0\beta(2-\tau)}{(\alpha-1)^3}\exp(-\alpha\tau), \quad (17)$$

$$y_2(t) = \frac{m_0\beta(\alpha\tau - \tau - 1)}{(\alpha-1)^2}\exp(-\tau) + + \frac{m_0\beta}{(\alpha-1)^2}\exp(-\alpha\tau), \quad (18)$$

where m_0 is the initial value of mediator concentration in the first synapse, $y_1(0) = m_0$. The initial values of the number of activated receptors in both synapses and the mediator in the second synapse are assumed to be equal to zero, i.e., $x_1(0) = x_2(0) = = y_2(0) = 0$.

In Fig. 2, the time dependences of the concentrations of mediator and activated receptors in both synapses, calculated in the linear approximation, are plotted. A numerical analysis demonstrates that the exact solution of the system of equations (9)–(12) for the same parameter values and initial conditions differs little from the results obtained within the framework of the linear model (13)–(14). The numerical solution of the nonlinear system with the initial condition $y_1(0) = m_0 = 0.9$ is shown in Fig. 3.

In Fig. 4, the phase trajectories are shown for the dependences of the concentration of activated receptors, x_2, and the mediator concentration in the second synapse, y_2, on the concentration of activated receptors in the first synapse, x_1. As expected, the trajectories are closed, which is obviously a consequence of the stability of the zero stationary state, which was discussed above.

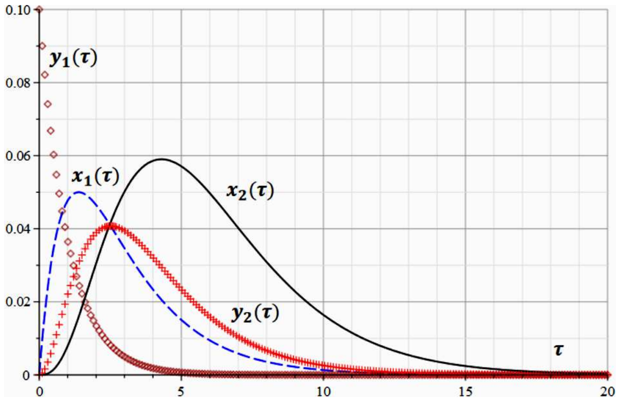

Fig. 2. Time-dependences of the model parameters in the linear approximation: $x_1(\tau)$ (dashed curve), $x_2(\tau)$ (solid curve), $y_1(\tau)$ (diamonds), $y_2(\tau)$ (crosses). $\alpha = 0.5$, $\beta = 1$, $m_0 = 0.1$

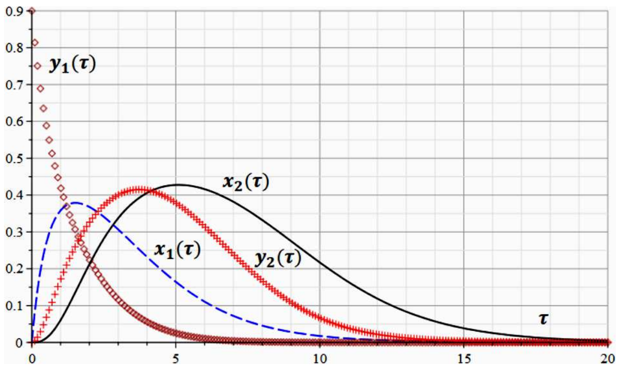

Fig. 3. The same as in Fig. 2, but for $\alpha = 0.5$, $\beta = 1$, $m_0 = 0.9$

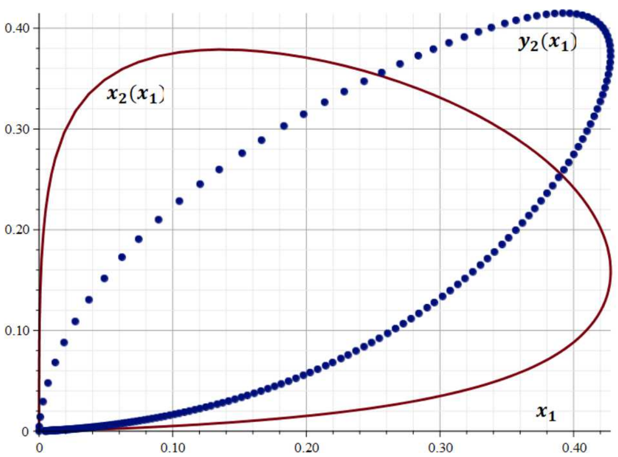

Fig. 4. Phase trajectories of the dependences of the concentration of activated receptors in the second synapse, x_2 (solid curve), and the mediator concentration in the second synapse, y_2 (spheres), on the concentration of activated receptors in the first synapse, x_1. $\alpha = 0.5$, $\beta = 1$, $m_0 = 0.9$

4. Signal Transmission

Since the main purpose of a synapse (or, in our case, a system of interacting synapses) is to transmit signals, the following question naturally arises: How is the signal transmitted through the researched system? In terms of the proposed model, this question can be reformulated as follows: How does the input signal, which is determined by the function $f_1(t)$ in Eq. (4), affect the dynamics of the parameter $r_2(t)$? In other words, we are interested in how the intensity of mediator injection into the first synapse affects the number of activated receptors in the second synapse. It is clear that only numerical analysis is possible here, so we will use dimensionless equations (9)–(12), with the function $f_1(\tau)$, which describes the intensity of mediator injection into the first synapse, being added to Eq. (10). Bearing in mind that rectangular model signals are usually fed to the input of neurons in physiological experiments, let us consider the function $f_1(\tau)$ in the form of a "unit column": a signal with a (dimensionless) amplitude of 1 and a (dimensionless) time length of 1, which begins at the time moment $\tau = 1$, i.e.,

$$f_1(\tau) = \begin{cases} 1 & \text{if } \tau \in [1;2], \\ 0 & \text{if } \tau \notin [1;2]. \end{cases} \tag{19}$$

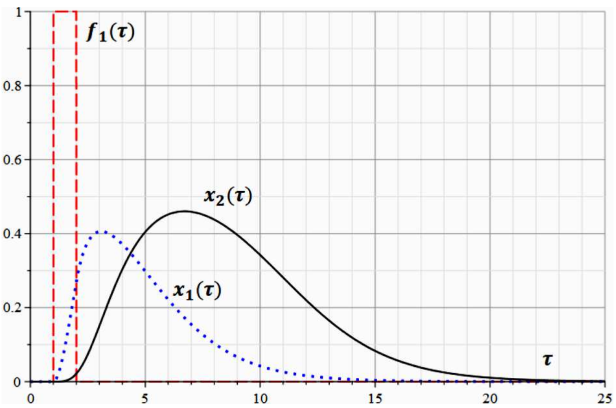

Fig. 5. Time dependences of the intensity of mediator injection into the first synapse, $f_1(\tau)$ (dashed curve), the concentration of activated receptors on the first postsynaptic membrane, $x_1(\tau)$ (dashed curve), and the concentration of activated receptors on the second postsynaptic membrane, $x_2(\tau)$ (solid curve)

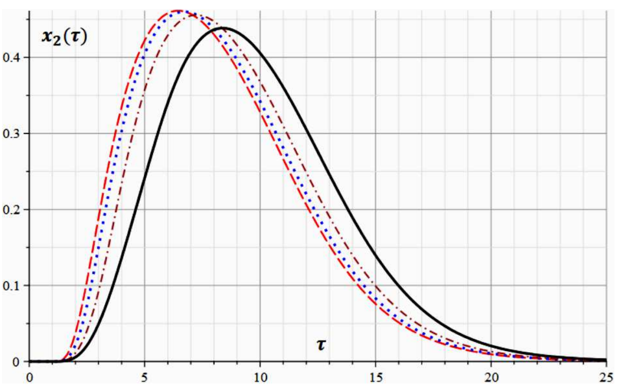

Fig. 6. Dependences of the concentration of activated receptors on the second postsynaptic membrane for various types of input signal at the first synapse (provided that the amount of mediator supplied to the synapse is constant, $AT = 1$): the signal amplitude $A = 2$ (dashed curve), 1 (dotted curve), 0.5 (dash-dotted curve), and 0.25 (solid curve)

In Fig. 5, the time dependences of the concentration of activated receptors in the first synapse, $x_1(\tau)$ (dashed curve), and the concentration of activated receptors in the second synapse, $x_2(\tau)$ (solid curve), are depicted against the background of the dependence $f_1(\tau)$. The following considerations are worth noting. Firstly, the activation of receptors in the first synapse affects the second synapse, but the activation of receptors in the second synapse does not affect the first synapse. Therefore, the first synapse works in the same way as if the second synapse were altogether absent. In this sense, when comparing the first and second synapses, we, in fact, compare a system consisting of one synapse with a system consisting of two synapses. Secondly, we can consider a system of two interacting synapses as a "black box", with the mediator being fed to the input and the concentration of activated receptors on the postsynaptic membrane of the second synapse being measured at the output.

By comparing the concentration of activated receptors in the first and second synapses, one can arrive at the general conclusion that the corresponding profiles are similar. However, there is a time shift between the profiles. This shift is not a result of the signal transmission through the synapse but of the inertia of the synapse interaction process. Moreover, it turns out that the system is quite stable with respect to changes in the input "signal" profile, the role of which is played by the function of the intensity of mediator injection into the first synapse, $f_1(\tau)$. Namely, if instead of the "unit column" (19), pulses of the form

$$f_1(\tau) = \begin{cases} A & \text{if } \tau \in [1;1+1/T], \\ 0 & \text{if } \tau \notin [1;1+1/T] \end{cases} \tag{20}$$

are considered, then the general profile of the time dependence of the concentration of activated receptors changes insignificantly when the values of the parameters A and T are varied under the condition $AT = 1$ (a constant amount of mediator supplied to the synapse), as shown in Fig. 6. This result is important at least in view of the prospects for carrying out experimental studies, since it allows a certain variability in the form and length of the signals supplied to the system input.

5. Conclusions

The model of two interacting synapses, proposed in the paper, brings us closer to understanding the processes occurring during the transmission of nerve signals through complicated natural neural networks. In practical aspects, the model can be useful because it provides a certain toolkit to analyze and interpret the results of experimental studies of signal transmission through neural chains. In theoretical aspects, the results obtained for the model are important, taking into account some circumstances. Firstly, according to the results, the presence of interaction between synapses (and, therefore, neurons in an artificial or natural network) does not affect the stability of the system as such. The system has a stable zero stationary state. This means that an insignificant random activity in the neural channel will not be amplified and will not distort the "useful" signal, for the transmission of which the neural network is actually intended. Secondly, the availability of an additional synapse affects the signal transmission process at a qualitative level in the sense that, on the one hand, it creates a time delay and, on the other hand, this "additional" synapse can, in principle and if necessary, play the role of a reinforcing element, which will positively affect the stability and reliability of the whole system. It should also be noted that the proposed model extends the understanding of the specific features of neural signal transmission and opens up new prospects for the creation of artificial neural-type systems.

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МОДЕЛЮВАННЯ ПЕРЕДАЧІ
СИГНАЛУ ЧЕРЕЗ СИСТЕМУ З ДВОХ СИНАПСІВ

У статті пропонується модель, яка описує процес передачі нервового сигналу через систему, що складається з двох взаємодіючих синапсів. Модель ґрунтується на нелінійних диференційних рівняннях, які описують активацію рецепторів на постсинаптичних мембранах двох синаптичних щілин. Взаємодія синапсів в рамках моделі реалізується так, що активація рецепторів на першій постсинаптичній мембрані визначає інтенсивність впорскування медіатора в другий синапс. Для такої системи вивчається питання щодо особливостей стаціонарного стану, який, як показано, є стійким. Також в статті досліджується вплив інтенсивності впорскування медіатора в перший синапс системи на концентрацію активованих рецепторів у другому синапсі. Показано, що на якісному рівні надійність усієї системи не порушується, а характер процесу активації рецепторів на постсинаптичній мембрані другого синапсу є стійким щодо варіативності вхідного сигналу.

Ключові слова: імпульс, синапс, медіатор, мембрана, рецептор, активація.