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Design of Nano-Scale Devices Affecting Synapses:

The New Approach to Artificial Intelligence and Brain Interface

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ABSTRACT

The research describes the nano scale devices, their general architecture, and how they affect the synapses. Such devices, based on the new approach in artificial intelligence, will play a significant role in many spheres. The research also describes the architecture of the programming neuron built on the basis of a biological one. Unlike existing technical devices for implementing a neuron based on classical nodes oriented to binary processing, the proposed path is based on bit-parallel processing of numerical data (synapses) for obtaining result. The proposed approach of implementing a neuron can serve as a new elementary basis for the construction of neuron-based computers with a higher processing speed of biological information and good survivability.

KEYWORDS

Algorithm, Artificial Intelligence, Axon, Brain, Dendrite, Nano, Nano Technology, Neural-Network, Neuron, Neuron Model, Nervous Circuit, Synapse

INTRODUCTION

Nowadays the sphere of Artificial Intelligence is based on the simplified programmable model of a neuron which becomes a basis of different topologies‘ neural-networks (Galiautdinov, R., 2019). Such the approach however does not seem to be able to fully resolve many problems and build fully functional Artificial Intelligence (Lee, H. et al., 2009 A). At the same time many different spheres have a demand of being able to connect neural activity of biological creatures and technical devices. The solution could be applied in medicine, military sphere, education, etc (Galiautdinov, R. & Mkrttchian, V., 2019 A).

The major trend in such the work was based on measuring of the electrical activity of the brain. Most of the researches in this sphere use the data received with the help of encephalogram adopting this data into some visible result (Lee, S.H. et al., 2017). The recent activity of some other researchers is based on injection of the small electrodes into the brain providing some kind of result based on human interpretation of the spikes (the data of the electrical activity of the brain). As we can see there is no significant difference. Moreover, such the approach leads to dead-end simply because of the two major factors:

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- The size of the electrode can't be reduced more than it's reduced now, because it would effect on the quality of the received signal (Ford, L. et al., 2019);
- The work of the brain is based on electro-chemical transfer of a signal and not just on the electrical signal (Hawkins, R.D. & Kandel, E.R., 2019). The electrical signal might be translated as "do something" and "stop doing something" and the researchers do not take this into consideration.

The approach suggested here is based on nano-scale devices which effect on the synapses and the whole interpretation of the neural activity requires the introduction of another type of the programming neuron based on the biological one which should become a new direction in the sphere of Artificial Intelligence (Galiautdinov, R. & Mkrttchian, V., 2019 B).

The new type of programming neuron (BN) could also become a basis in development of the computers.

The problem of remote control and monitoring of biochemical processes at the molecular and nanoscale level is extremely important and is significant in various fields of science and technology (Rayman, J.B. & Kandel, E.R., 2017). Nanotechnology offers a number of new approaches for this, in particular, the use of composite magnetic nanoparticles activated by an external low-frequency non-heating magnetic field with a frequency of <1 kHz (Mkrttchian, V., Gamidullaeva, L. & Galiautdinov, R., 2019). In this case, magnetic nanoparticles act as mediators that convert the energy of an external magnetic field into mechanical stimuli that transform into a controlled deformation of the surrounding macromolecules and macromolecular systems, thereby changing their structure, properties and biochemical activity.

This approach has significant potential for the selective management of biochemical reactions (regulation of kinetics, yield ratios, cell survival) and the creation of new generation chemical molecular technologies, in particular, for solving nanomedicine problems with molecular locality, selectivity and targeted therapeutic effect (Asok, A. et al., 2018).

Computer Neuron

The artificial or programming neuron used in Computer Science partially simulates the biological neuron. Such the artificial neuron receives the number of the signals as the input data and each of these signals is in fact the output of another neuron (Fiumara, F. et al., 2016). Each input gets multiplied by the appropriate weight (simulating the synaptic strength) then we can sum all the values and define the level of neuron activation. The final result of this operation would be either 0 or 1.

There are different kinds of the neural networks but all of them are based on the above described configuration. There are multiple input signals for the artificial neuron: $x_1, x_2,\ldots,x_n$ .These input signals correspond to the input signal in the synapses of the biological neurons. Each signal gets multiplied by the appropriate weight $w_1, w_2,..,w_n$, and then all of them get redirected to the summation block marked with a symbol $\sum$. Each weight corresponds to the power of a single biological synapse. The summation block which corresponds to the body of the biological element, arithmetically sums the inputs and creates the output R.

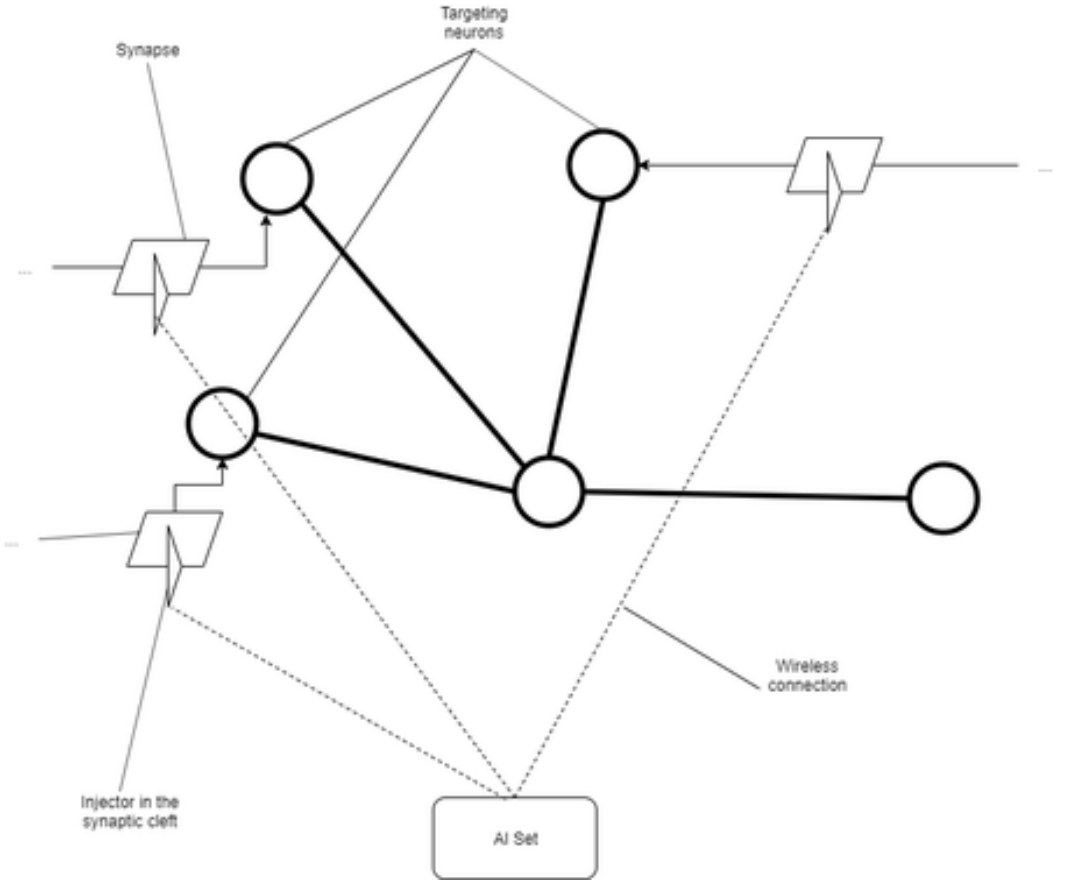
Such the description can be defined with the following formula:

$$R = \sum_{i=1}^{n} W_i X_i + W_0$$

where:

W_0 – is a bias
W_i – is the weight of the i^{th} neuron

Figure 1. Illustration of the artificial neuron



x_i - is the exit of the i^{th} neuron
n – is the number of the neurons, which serve as the input for the processing neuron

The signal W_0 which has a name "bias" represents the shift limit function. This signal allows you to shift the origin of the activation function, which subsequently leads to the increase in the learning speed. This signal is added to each neuron, it learns like all other scales, and its feature is that it connects to the +1 signal, and not to the output of the previous neuron. The received signal R gets processed by the activation function and returns the output signal X (Figure 2).

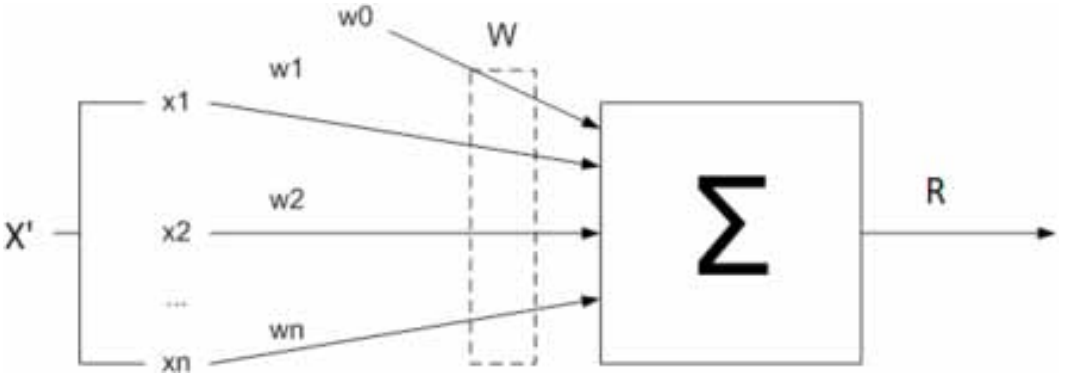
The function F is called a function which narrows in the case the activation function narrows the range of variation X so that for each value of R the value of X belongs to some range of the final interval. For this usually we use the logistic function. This function can be described in the following way.

The major advantage of such the function is that it has a simple derivative and differentiates along the abscissa. The function increases the weak signals and reduces "too strong" signals.

There is also another function that is frequently used is hyperbolic tangent. It resembles a sigmoid in shape and is often used by biologists as a mathematical model of nerve cell activation. It looks in the following way:

$$x = th\left(R\right)$$

Figure 2. Illustration of the artificial neuron with the activation function



Like the logistic function, the hyperbolic tangent is S-shaped, but it is symmetrical with respect to the origin, and at the point of $R = 0$ the value of the output signal $X = 0$.

The Principal of Work of the Nervous System

The signals between the neurons are not just electrical, they are electro-chemical. One of the neural processes which describes the mechanism of memory's work is called summation. This process and the new method of receiving the information based on the neurotransmitters was described in the details in the research of Galiautdinov (Galiautdinov, R., 2020). Describing the process of summation it's known that the major key of the process is enclosed in the fact that weak but frequent enough signals can eventually make the signal "to jump" to another neuron in the neural circuit and the mechanism of this process is based on collection of the calcium ions. The memory based on this mechanism does not last long and the information received through the usage of this mechanism disappears as soon as the calcium ions "disappear".

Another very important neural process which is related to the memory mechanism is called Long Term Potentiation. The mechanism starts in the case if there was a strong enough signal (~ -30mV) which makes the receptors "to spits out" the ion of Mg2+.

And one more example of how the memory works is so called "Papez circle", which represents some kind of neural circuit's connected route in the brain and runs the signal in the circle.

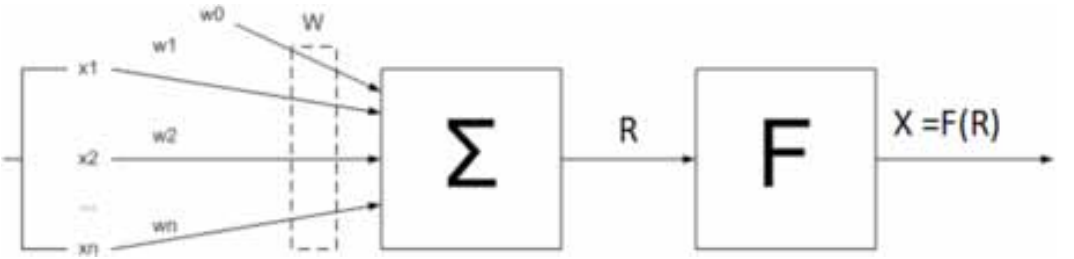
Mathematical Model of Biological Neuron

The mathematical model of biological neuron is represented in Figure 3.

Let's consider the beginning vector which is located in the center of the active stand and the end is directed to the pattern point defined for a given neuron. Denote it as the vector of the preferred direction of the excitation's propagation (T, trend). For the case when the vector T is in the biological neuron it can manifest itself in the structure of the neuroplasm, perhaps these are the channels for the movement of ions into the body of the cell, or other changes in the structure of the neuron. A neuron has the property of memory, it can memorize the vector T, the direction of this vector, can change and overwrite depending on external factors. The degree to which the vector T can undergo changes is called neuroplasticity.

This vector affects the functioning of the neuron synapses. For each synapse, we define the beginning of the vector S which is located in the center of the cell, and the end is directed to the center of the targeting neuron which is connected to the synapse. Now the degree of influence for each synapse can be determined as follows: the smaller the angle between the vector T and S is, the more the synapse will be amplified; the smaller the angle, the stronger the synapse will weaken and may possibly stop the transmission of excitation. Each synapse has an independent memory property;

Figure 3. The mathematical model of biological neuron



it remembers the meaning of its strength. The indicated values change with each activation of the neuron, under the influence of the vector T, they either increase or decrease by a certain value.

The input signals $(x_1, x_2, ... x_n)$ of the neuron are real numbers which characterize the strength of the synapses of the neurons which affect on the neuron.

A positive value of the input means a stimulating effect on the neuron, and a negative value means an inhibitory effect.

For a biological neuron, it does not matter where the exciting signal came from, the result of its activity will be identical. A neuron will be activated when the sum of the effects applied on the neuron exceeds a certain threshold value. Therefore, all signals pass through adder (a), and since neurons and the nervous system work in real time the effect of the inputs should be evaluated in a short period of time. The result of the adder passes the threshold function (b) and if the sum exceeds the threshold value then this leads to neuron activity. A neuron sends a signal of its activity to the system when neuron gets activated. The information includes its position in the space of the nervous system and the charge that changes over time (c). After a certain time after the activation, the neuron transmits excitation along all the available synapses. Before such the transmission the it recounts the strength of the available synapses.

The vector T (d) is adjusted taking into account the value of the pattern point Pp and the level of neuroplasticity. Next, there is a reassessment of the values of all synapse forces in the neuron (e).

Note that blocks (d) and (e) run in parallel with block (c).

The next simplification of the Hodgkin-Huxley model is the Morris Lecar model, proposed in 1981. This system of equations describes the complex relationship between the membrane potential and the activation of the ion channels in the membrane. Mathematically, the model is written as follows.

The open state probability functions MSS (V) and WSS (V) are obtained from the assumption that open and closed states of the channels are delimited according to the Boltzmann distribution. Changes in the external current, I, are accompanied by a saddle-node bifurcation, leading to the birth of a limit cycle. In the field of theoretical modeling of neural oscillators the independent researcher Galiautdinov R. is developed the number of the new math models of neural dynamics.

One of the most interesting developments is the model of the modified FitzHugh-Nagumo generator, which is a simplified version of the Hodgkin-Huxley model. This model has a separatrix threshold manifold that separates signals into subthreshold oscillations and suprathreshold excitation pulses, which are further used for communication between neurons. In addition, the model simultaneously possesses the properties of an integrative response typical of threshold systems and resonance characteristics similar to oscillatory systems. In other words, there is a fundamental possibility of simultaneously performing both frequency and phase encoding and decoding of information.

Previously, the author of the model of the modified FitzHugh-Nagumo generator proposed a model of a neuron with spontaneous periodic oscillations below the excitation threshold. The model is based on well-known dynamic systems and is described by a system of fourth-order differential equations.

Figure 4. The model describes the complex relationship between the membrane potential and the activation of the ion channels in the membrane

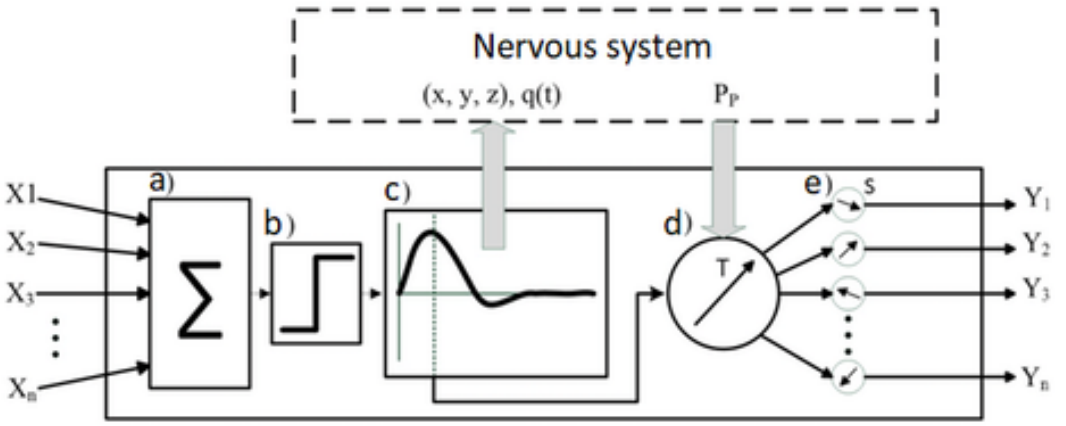


Figure 5. Illustrates phase plane of the FitzHugh-Nagumo model with a threshold manifold

$$\begin{cases} C\dfrac{dV}{dt} = I - g_L(V - V_L) - g_{Ca}M_{SS}(V - V_{Ca}) - g_K N(V - V_K) \\ \dfrac{dN}{dt} = \dfrac{N - N_{SS}}{\tau_N}, \end{cases},$$

$$M_{SS} = 0.5(1 + \tanh[\frac{V - V_1}{V_2}]),$$

$$N_{SS} = 0.5(1 + \tanh[\frac{V - V_3}{V_4}]),$$

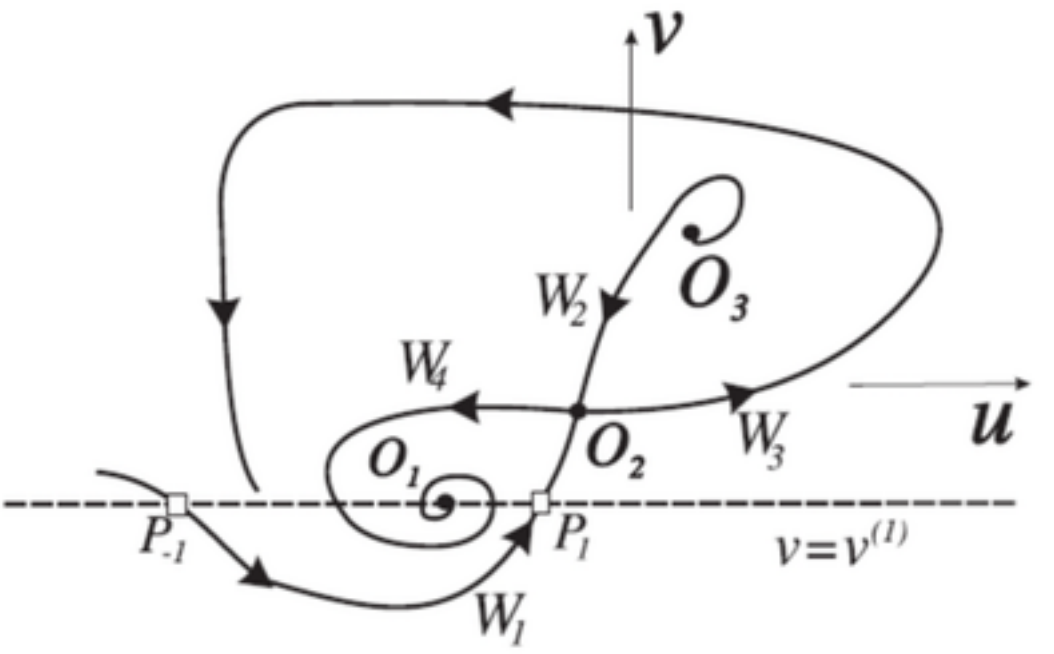
$$\tau_N = 1/(\phi \cosh[\frac{V - V_3}{2V_4}]),$$

The first block describes subthreshold oscillations and can be implemented as a Van der Pol generator in a soft excitation mode. The second block is responsible for the formation of an impulse and is implemented as an excitable FitzHugh-Nagumo element. Introducing a nonlinear connection between the blocks, we conclude that the dynamics of the model can be described by the following 4th-order system (Figure 7).

The variables x and y describe the dynamics of the first block:

u, v – of the second one

Figure 6. Illustrates model of an excitable element with subthreshold oscillations. Functional diagram.



f(u) – nonlinear function of cubic form
ε1, ε2 – small positive parameters
I – constant external stimulus

γ, β, l > 0, α < 0 – the parameters characterizing the dynamics of Van der Pol variables and the relationship between blocks (Galiautdinov, R. & Mkrttchian, V., 2019 B)

Nano Technology in Interpretation of the Nervous System

Here the author describes his own approach and the experimental part which proves that this is a working approach (Galiautdinov, R., 2020).

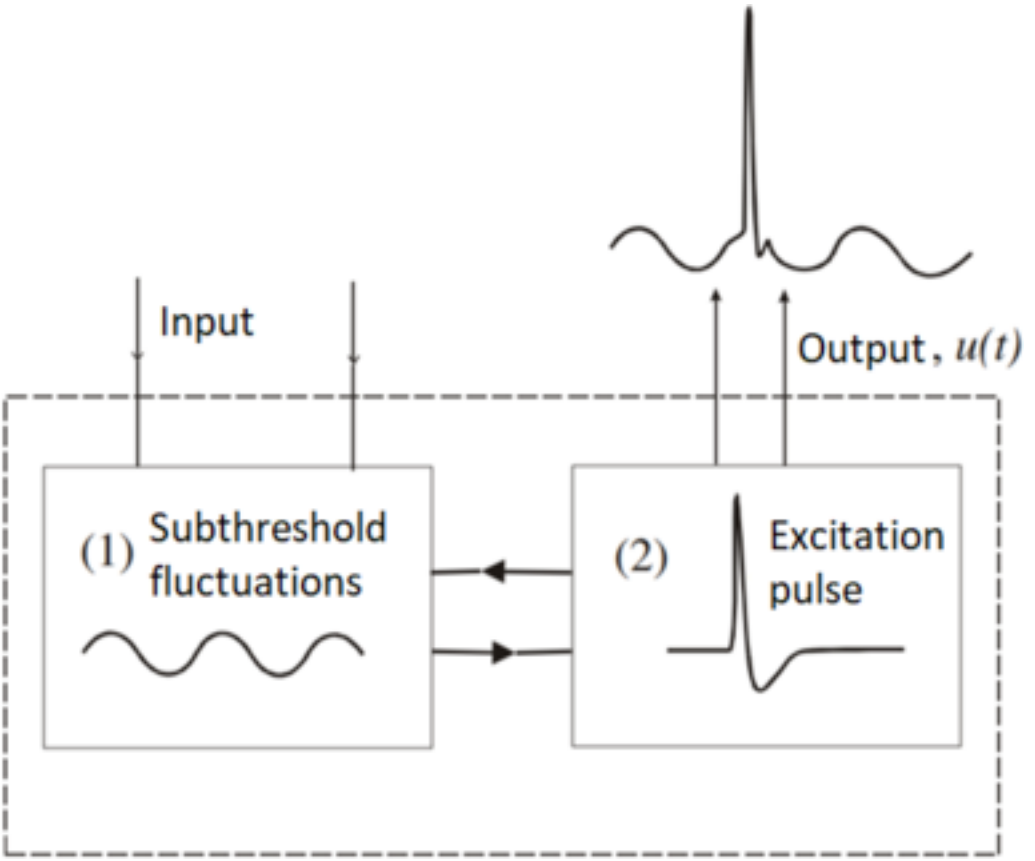
Usually the reason of paralysis is that a signal of the neuron somewhere in the brain can't reach the motor-neuron which effects on the muscle. Strictly speaking the signal gets stopped somewhere because of the biological injury.

Consequently in order to resolve this problem it's necessary to catch the Action Potential (AP) either in the source point or somewhere on its way to the destination and either simulate it effecting on the motor neuron or simulate directly the muscle based on the signal and type the neuron sent. However, we can't just measure the electric charge somewhere and reproduce the same electric charge in the destination point: such the approach has a dead end, not accurate and will not work the way we need.

Before we make any kind of the signal interpretation it's necessary to understand the type of the neurotransmitters causing the signal (~80%: either Glu or GABA, ~20% the other types of neurotransmitters with the count of 20+), the strength of the signal (to distinguish the type of the running process: summation, long lasting potentiation) and the source point of the signal.

It's impossible to find out what kind of neurotransmitters are involved into the signal by checking only the AP of big enough and random areas of a brain. It is required to have some indicator within the synaptic cleft in order to find out this. This indicator would chemically evaluate the neurotransmitters types in the synaptic cleft and the time interval they get in. Another indication which is necessary for

Figure 7. The 4th-order system that describes the dynamics of the model



resolving the task is the detection of what kind of receptors are used: NMDA or Non-NMDA, but this could be resolved by the analysis of the caught transmitters.

The indicator which is supposed to gather the information regarding the neurotransmitters and transfer the signal must be of 5-8nm which means we are talking about the nano-scale technologies. Such the technology does not exist at the moment. However, the general architecture is described in Figure 8.

Without having such nano-scaled device, for the experiment the author used an Aplysia (the mollusc) and considered the reflex chain of 24 sensor neurons leading to 6 motor neurons of the gills. However, in this particular experiment it's not necessary to consider the whole chain, it would be enough to limit the consideration to only 2 linked neurons: one sensor neuron and one motor neuron. The difference of the author's experiment and the experiment of Eric Kandel (Kandel et al, 2019) is enclosed in the following: the author's goal was not to research the process of summation, but to catch the emitted neurotransmitters and estimate whether the analysis of the neurotransmitters would allow to evaluate the running process and effect on the muscle.

Thus, gathering the information about the neurotransmitters is something what could be quite difficult to do at the current level of technology. The most modern indicator has a width of around 80nm which is too much for a synaptic cleft which has a width of 10-50nm.

Taking into the account the current level of technology, we can't insert some indicator inside of a synaptic cleft of a working synapse. That's why for the goal of the experiment the author decided to use another approach: instead of inserting the indicator inside of a synaptic cleft, the author cuts the

Figure 8. The general architecture of the neurotransmitter

$$\begin{cases} \varepsilon_1 \dot{u} = f(u) - v - y; \\ \dot{v} = \varepsilon_2 (u + I), \\ \dot{x} = y, \\ \dot{y} = (\gamma(1 + \alpha I + \beta u) - l x^2) y - \omega_0^2 x, \end{cases}$$

synapse on a level of its synaptic cleft and placed a piece of glass on a distance of 40nm from the cut, so that this piece of glass would simulate some kind of a postsynaptic membrane. Additionally, for the experimental part the neuron was connected with the electrode in order to measure the AP. Then the author stimulated the sensor neuron effecting on the gills which led to emission of neurotransmitters on a glass playing the role of a postsynaptic membrane (Galiautdinov R. 2020).

The analysis of the chemical substance was then done with the help of High Performance Liquid Chromatography (HPLC) (Galiautdinov R. 2020).

This experiment allowed to catch the neurotransmitters of the synapse when it was working and detect the type of the emitted neurotransmitters. During the experiment the distance between the synaptic cut and the glass was varied between 10-40nm. The best result was achieved on a distance of 10-15nm.

In the initial sets of experiments the goal was to prove with the experiment that catching of the neurotransmitters could be done and the caught neurotransmitters could be defined. All this was proved by the experiment. The analysis showed the ability to distinguish the neurotransmitters and to define Glu (C5H9NO4) in this particular experiment.

Catching the neurotransmitters allowed to assess the type of the neurotransmitters used and the approximate quantity. The further potential experiments with the quantity of neurotransmitters are quite useful and would allow to distinguish the running process: summation or long lasting potentiation.

The data was analyzed according to the described above method for assay determination of some amino acids in the joint presence of and in combination with natural bioactive components by high performance liquid chromatography (HPLC) in the reversed - phase variant with UV detection.

Then the data was automatically stored in the database and contained 3 fields for each experiment: the approximate quantity of the neurotransmitters, the type of the neurotransmitter and the value of the AP on the electrode. The running application allowed to find the correlation between the quantity and the AP and make prediction of the following result. At the final stage, having the calculated AP the system can effect on the synaptic membrane which could arouse the next neuron in the neural circuit.

Such the implementation can be and was already simulated with the help of the Neural-constructor developed by Galiautdinov (Galiautdinov R., Mkrttchian V., 2019 A). The neural circuit of Aplysia (the mollusc) was built with the help of the Neural-constructor and simulated the influence of the input signals on the work of the neural circuit and received the output signal which was able to effect on the virtual muscles (Galiautdinov R., Mkrttchian V., 2019 A).

The programming model of the artificial neuron was based on the biological model contains the following key features:

- Each artificial biological neuron has generic list of the Queues for dendrites (input signals) and axons (output signals);

- Each synapse can generate the vesicles containing different type o neurotransmitters (in my research I used only 2 neurotransmitters: Glu, GAMA). The generation of the vesicles starts when the neuron receives the AP which can be instantiated based on the signals received from the Queue(s) of dendrite(s). Such the signal is not constant and depends on the quantity of neurotransmitters caught by the synaptic membrane (for the case if summation process runs – Non-NMDA receptors were triggered) or it's constant enough even with the small quantity of neurotransmitters for the case when NMDA receptors were targeted and one of the initial signals was strong enough (Galiautdinov R., 2020);
- Each axon can have only one type of neurotransmitters;
- The programmable synapse can generate the calcium ions coming inside and simulate the process of interaction with the vesicles, which effects on simulation of moving of the vesicles towards the synaptic membrane and emission of neurotransmitters into the synaptic cleft which will effect on initiation of the signal in another neuron;
- The emitted neurotransmitters do not affect directly on another neuron, they effect on the synaptic membrane which is programmatically represented as an input object of the dendrite connected with another neuron. The emission result fully depends on the type of the receptors and the whether NMDA receptor (if this is a case) is "turned on" (what could be caused by the initial strong signal).

Such the approach was used by Galiautdinov in creation of the neuron-based constructor in the beginning of 2016. This neuro-constructor allows to construct the neural circuits including the virtual muscles and virtual sensors. The virtual sensors serve as a triggering mechanism effecting on the neural circuit and the virtual muscles serve as outcome. Each neuron and each synapse generate the logs, which includes the data of the APs, the number of emitted calcium ions, the number of instantiated vesicles with neurotransmitters, the number of emitted neurotransmitters, the type of the receptors and the data related to the newly generated signals. This constructor allows to move the experiments on biological objects (such as Aplysia – the mullusc) into the virtual sphere where no animal is necessary for exploring of the work of the nervous system. More important, it allows to construct extremely complex virtual neural circuits and research its behavior. Such the approach allows to simulate the nervous system even of the complex creatures. During the experiment, with the help of the author's neuro-constructor, the nervous system of Aplysia and Planarian (Tricladida) was virtually created. The generated neural circuit was able to simulate the work and behavior of the natural creatures.

CONCLUSION

In this study, the author considered the modern tendency in the sphere of brain interfaces, and highlighted that the current approach that offered by such companies as Neuralink leads to the dead end. The author suggested another technology and method that based on the nano-scale devices effecting on the synapses, where on one hand has a specific way to go, and on another hand can be improved with the growth of technology. The suggested method however is quite difficult to reproduce because of the required level of technological equipment that needs to be used during the physical part of the experiments. Although the experiment was considered as successful there is still a number of the additional research required to go towards the development of the suggested nano-scale technology.

With regards to the technological demand, one of the major challenges is enclosed in operations on a nano-scale level. The author also considered the difference between artificial programmable neuron and the biological one, showing the difference and how this difference effects on the number of the neural processes in the nerve system of a biological/artificial creature.

The discussed study described the experiments implemented on the virtually created neural circuits with the help of the neural constructor developed by the author. Such the virtual experiments

have the boost to growth of the science since these experiments are not limited by the lack of the technical equipment and biological materials and at the same time the achieved result is pretty much closed to the result which could be achieved in a lab working on the physical equipment with the biological materials.

The described nano-scale device and technology however have a wide range of the practical use, especially in the medical, IT and military spheres. The author described the high-level architecture of the nano-scale device which could be used for analysis of the neurotransmitters and detection of how and when to effect on the following neurons in the neural circuit. It is demonstrated in this research that it's possible to get the proper interpretation of a brain signal and effect on the muscle even in the situation when neural circuit is corrupted.

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