The paper considers the neural memory of the human brain from the viewpoint of visual information processing. A model that explains the principle of data recording and storing, memory relaxation, associative remembering and other memory functions is offered. The model of associative memory is based on the methods of holography, "wave biochemistry" and autowaves. Brief consideration is given to the associative properties of holographic neural structures and the memory architecture using running chemical reactions.

The paper also outlines the problem of developing artificial memory elements for restoring the brain functions and possible interface devices for coupling neurons to electronic systems.

1. Introduction. Statement of problem

A man receives most of information visually. The rate at which the visual information comes in can be estimated at about $10^8$ bit/s ($10^6$ receptors times 100 bit/s). Therefore, the amount of information a man acquires over his lifetime is about $10^{14} - 10^{16}$ bits. If we take into account only fresh information, it makes a part of this value (a few orders of magnitude at least). Clear that only a small portion of this information is stored.

It is interesting to evaluate the capacity of archive (long-time) memory of a grown-up. Assuming that a man knows about 300 thousand words, notions, objects (quite large dictionary) each of 50-70 bit, we get the storage capacity of about $10^7$ bit. Also add a few thousands "images" (pictures, melodies, faces, smells, sounds, etc.). The result is $10^8 - 10^9$ bits\(^1\). We see that capacity of the archive memory of a grown-up makes just a small portion of

\(^1\)We suppose that the brain stores just a small portion of the information the "image" holds. Everyone can easily test yourself by remembering, for example, of a particular picture: only few details that distinguish it from another image can be restored. These details make thousandths of a percent of all the information the "image" holds [2].
the data a conventional laser disk carries. That is why an idea comes to develop an artificial memory element that can be implanted in the brain and powered from living cells [1,2].

The task of developing artificial memory elements would dramatically increase the efficiency of mental capabilities. It is especially important for old people whose memory deteriorates rapidly because of the dying of cerebral cells and intercellular links.

Clear that tackling a serious problem like that calls for the understanding of the biological memory principles. In particular, it would requires:

- research into physical, chemical and biological processes of perception, data storage and retrieval, relaxation and erasing;
- development of neural memory models;
- development of artificial neural memory elements;
- development of the interface between biological neuron and artificial memory element;
- development of inner power supply for implanted memory elements;
- development of the control interface;

The research activity should go together with development of corresponding hardware such as combined multifunction nanocircuits (bioelectronic, optochemical, plasmon, acoustoholographic, optomechanical etc. chips).

3. Neural memory peculiarities

The ability to distinguish necessary information from visual and sound patterns, and from various smells and touches is a distinctive characteristic of animate nature. A man can recognize people, things, and images easily and unconsciously. He effortlessly discriminates necessary information from heavy noise. For example, when he listens to an orchestra playing, he can tune his ear to a violin or any other instrument and follow its part despite of the “roar” of the whole orchestra.

Another example: butterflies can recognize one another at great distances (a few kilometers) by discriminating microscopic concentrations of pheromone molecules (about 1000 molecule/cm$^3$) produced by a female from $10^{19}$ molecule/cm$^3$ of the air (which can be regarded as a very high “noise level”).

The important distinction of neural memory is associative data retrieval. When a piece of information is needed, the system addresses the whole memory array (in contrast to going to a particular memory cell in conventional computers) and retrieves data associatively, using
a certain criterion. A good example of associative retrieval: we can recall a melody after hearing its piece, and the flavor of a flower brings back memories.

Associativity of a neural net, as well as a hologram suggests that any of its portion can be used to find and restore necessary information. It is because neural and holographic systems, like any living system, are intrinsically associative. Using associations, a man can easily restore a sequence of space-time events and find in his brain the information that he could not remember a minute ago.

A great number of neurons determine data-processing capabilities of the brain. The neurons can process input information by transforming it into electrical and chemical signals and transmitting them over the nervous system – the communication network of the brain. Unlike common data-transmission systems, electric and biochemical processes in the brain are closely linked and data transfer involves various chemical reactions, including non-stationary, nonlinear, relaxation and autooscillation phenomena.

Therefore information circulates in a more complicated way than in well-known radio and optical communication systems.

Fig.1 gives a simple schematic drawing that helps to understand data transmission between neurons.

![Fig. 1 Signaling in neural network](image)

Each biologic neuron has a cell body the inner part of which is separated from the external medium by a 4 to 7-nm thick membrane and carries an electric potential of \(-70\) mV
relative to it in the quiescent state. When a cell is excited, its inner potential changes the sign and grows to +40 mV in a few milliseconds. The excitation (potential pulse) begins to travel down the axon (unidirectional connection line). The axon branches end has many thickening tips – synapses, which go to other neurons or their dendrites (short outgrowths). In terms of communication lines, dendrites can be regarded as unidirectional data-receiving lines.

Each neuron uses synapses to receive signals from many other neurons. One type of signals tries to excite the neuron, the other prevents excitation. When the total signal exceeds a certain threshold, the neuron gets excited: it generates a new signal (potential pulse) which propagates down the axon as an autowave (a running pulse). The signal comes to the synapses (numerous ends of the axon) and is transmitted to other neurons in a chemical way through the synaptic gap (a narrow separation about 20 nm wide between the axon end and receiving neuron or its dendrite).

After reaching the axon end, the electric pulse causes synaptic vials to burst and send neurotransmitters (special agents that diffuse to the receptors of destination cell) to the synaptic gap. Depending on the neurotransmitter type, the receiving cell either gets excited or not. Excitation means that information (nervous pulse) goes further to the next group of the neural network.

Therefore, the biologic neuron has a unique ability to receive, process, and transmit information. In neural systems it is often hard to understand where the signal generation area ends; as in autowave systems, propagation is sometimes accompanied by generation processes. Moreover, electric and biochemical effects are closely mixed up, and signal transmission is accompanied by various chemical reactions in which non-stationary, non-linear, relaxation, self-oscillation processes play a significant role. Signals travel at different velocities in different areas of the nervous system, which makes attempts to build the theory of nervous signal transmission still more difficult.

When discussing models of data recording, storage, and retrieval, it is helpful to formulate the following important properties of biologic neural nets in terms of physics:
- each neuron can be regarded as a generator of electric potential autowave;
- usually connected to one another, neuron-generators should be considered as a system of coupled generators (see Fig. 2);
- having many input/output data lines, each neuron is in fact a data transceiver rather than generator;
- input/output data lines are usually unidirectional;
- electric potential variation, frequency modulation, bistable oscillations and other sophisticated phenomena typical to biological autooscillation systems can serve as data signals;
- data rates usually vary from mm/s to m/s;
- propagation loss is a non-linear function of signal energy.

Fig. 2 Connections of neurons - generators

3. Information model of neural memory

What is presented below is one of possible models.

3.1. Data recording and storage

When a man sees something (e.g. a picture) the neural net gets excited and forms a "memory cluster" of closely coupled neurons. By way of example Fig. 3 shows a few memory clusters. Each cluster comprises some columns and "memorizes" the input pattern, after which the net comes to a new stationary state (with visual excitation, this takes fractions of a second). Another image results in another neuron cluster, etc. The clusters can overlap, sharing some neurons. Showing only two columns, Fig. 3 gives a good example of the process.
We see that the memory of each input image is distributed in a certain volume (just as holograms do).

Fig. 3 Memory contours by the example of two columns

If memory cluster is formed from weak excitation, they tend to relax away with time. With heavy excitation, synapses may pass the "linearity threshold" and retain modified. Then the memory of the image can keep for a long time until aging, a disease or any other stress destroys the memory cluster.

3.2. Reconstruction of information

It is evident that the excitation of any neuron belonging to a particular "memory cluster" will recall the information as in the case of hologram reconstruction.

3.3. Associative remembrance

It is clearly seen in Fig. 3 that a certain neuron belong to the different memory clusters. That is why "jumps" from one cluster to another are quite possible. This effect explains the sequence of associative remembrance so typical for our brain.
4. Holographic model of memory

In this chapter we examine the holographic model of memory, which helps to understand the analogy with the brain memory.

If we illuminate a few objects with laser light (Fig. 4) and record the scattered light on a photosensitive material, we get a hologram. Resulting from interference of light waves scattered by the objects, a hologram holds information about each of them. If, for instance, we want to restore the image of object 2, we should light the hologram with waves coming from object 1 and 3. If we illuminate it with the light arriving from object 1, we get images of object 2 and 3\(^2\). It is important that holographic restoration is possible even if there is only a small fraction of an original hologram.

**Fig. 4** Associative properties of holograms

Explanation of the phenomenon is that each bit of information is recorded over the whole surface of the hologram (or in every part of the three-dimensional medium). That is

\(^2\) we consider the general case [3]. When recording a hologram of a single object, we usually use reference and object waves, though the both are equivalent (as with heterodyning or frequency mixing).
why each small portion of the hologram holds all information about the object, though not very distinct (the larger the portion, the greater the correlative accumulation of the output signal and the better its quality).

The similarity between associative properties of holographic memory and neural memory of living beings looks attractive.

Fig. 5 shows a well-known holographic system for associative data retrieval that has a data bank of reference patterns and works like a neural network. The system has two identical holograms that hold overlapping holographic patterns each recorded with its own reference wave (Fig. 6 shows an arrangement where the reference beams has different directions). When the system tries to recognize an input pattern, it performs associative reading from the first hologram. All initial reference waves are restored with intensities proportional to the amplitude of the correlation function between the input image and reference patterns. Then the reconstructed reference beams are detected with an array photodetector. The detector output is coupled to the nonlinear amplifier, which amplifies the most intensive signals and
damps the others. The resulting electric signals are converted back to optical beams with a multichannel light modulator. The beams arrive at the second hologram and reconstruct the corresponding reference patterns, which go to the system input to start the whole procedure again. The result of this iteration process is the pattern that best corresponds to the input image.

Fig. 6 Image recording using hologram superposition. The direction of the reference changes each time a new hologram is recorded, which allows independent read out.

5. “Optobiochemical” process as the possible cause of memory clusters exitation

Today's artificial memory systems have external addressing and write and read information using external power supply.
Biological memory systems draw energy for data recording from internal supply\(^3\). It is important to notice that the recording medium itself serves as addressing system. Self-addressing of biological memory systems involves little-studied processes of self-organization, which do not obey the laws of thermodynamic equilibrium.

To understand what stimulus or signal and how excites a particular memory cluster, we will follow the principles of holography in our consideration.

Let an input image be a part of a reference pattern that is kept in a particular memory cluster of a neural network (see Fig. 3). Detected by receptors, the image goes to the neural net where the neurons (and synapses) belonging to the memory cluster that holds the corresponding part of the reference pattern get excited biochemically. Then the whole cluster gets excited and the whole image is reconstructed (as in the case of hologram).

The idea of using the principles of holography to explain the nature of associative memory had been mentioned firstly in our paper [3] (in mid-sixties). However, understanding the work of the brain requires us to take a next step forward: we ought to introduce and explain such notions as "coherence of chemical signals", "interference of chemical components" in reactions, "orthogonality of biochemical signals" and many other things typical to "wave biochemistry". As a good illustration of the approach, below we describe the use of "running" biochemical reactions for data recording/reading in systems where the recording medium itself serves as an addressing system [4-5].

6. An example of memory using running chemical reactions

We call the memory like that "optobiochemical memory" [6]. It needs a medium capable of generating a "chemical signal" in the form of running auto-wave pulses. The medium must be light-sensitive in the immediate vicinity of the pulse.

It is known that an oscillating chemical reaction can induce in a small area a concentration wave – a local "chemical pulse" that travels at a constant velocity without dispersion loss and triggers coupled chemical reactions. If the biochemical medium lies on a metallic substrate (Fig. 7), the chemical signal can change into electric one by bioelectric catalysis. If we could make the resulting substance light-sensitive, it would allow data recording.

---

\(^3\) The brain takes only 20% of all oxygen that energizes a man. Knowing that a man consumes 2000 kcal a day (i.e., 8400 kJ), which corresponds to average power of 100 W, we get 20 W for the brain.
Fig. 7. Memory based on running chemical pulses

Note again that the operation of memory when in the result of system self-organization every bit of information is stored by the whole medium is very similar to the memorizing processes of the human brain.

The possibility of such memory systems to read and write information was proved experimentally [4-6]. An oscillating chemical reaction was investigated. The reaction exhibited positive feedback (see the top part of Fig. 8) and gave rise to a concentration pulse in hydrogen peroxide (H$_2$O$_2$).

In the beginning, the concentration of hydrogen ions (H$^+$) is raised locally by either injecting acid in the solution or using electric discharge. A hydrogen ion sets glucooxidase ferment (E$_1$) to the active state (E$_1$H$^+$). Then the main reaction starts: oxidation of glucose (C$_6$H$_{12}$O$_6$) followed by formation of gluconate acid and hydrogen peroxide. The production of the gluconate acid increases the number of H$^+$ ions (due to reaction C$_6$H$_{12}$O$_7$↔ H$^+$ + gluconate), which accelerate the main reaction because of positive feedback.

At the same time the effect of another ferment E$_2$ (catalasa) causes partial dissociation of hydrogen peroxide (H$_2$O$_2$) and liberation of oxygen (O$_2$). That way, in a particular domain, the concentration of hydrogen peroxide (H$_2$O$_2$) grows to the maximum and then, when supply of oxygen or glucose is exhausted, falls to zero (time-dependence of the H$_2$O$_2$ pulse amplitude is presented by the top curve in Fig.8). However, due to diffusion of hydrogen ions, the reaction moves to the next domain, forming a running chemical signal – concentration wave of hydrogen peroxide.

Concurrently, the presence of peroxidase ferment (E$^{act}$) stimulates the bioelectrocatalysis reaction. This ferment is used by the medium to “pull” electrons from the
conducting substrate, thus producing an electric potential. The effect happens each time the running pulse of hydrogen peroxide contacts molecules of transformation-inducing peroxidase ferment (E_{act}). The corresponding chemical reaction is given in the middle of Fig.8. Experiments show that the positive potential of the electrode can reach hundreds of millivolts in this case. Molecule E_{act} becomes intact in the process.

\[
\begin{align*}
\text{C}_6\text{H}_{12}\text{O}_6 + \text{O}_2 + \text{H}_2\text{O} &\rightarrow \text{C}_6\text{H}_{12}\text{O}_7 + \text{H}_2\text{O}_2 \\
2\text{H}_2\text{O}_2 &\rightarrow 2\text{H}_2\text{O} + \text{O}_2
\end{align*}
\]

Fig. 8. Chain of photoelectrochemical reactions in the model self-addressing memory system. The ferments immobilized in gel are shown at upper right.

However, once photosensitized, ferment breaks down when light and a running H$_2$O$_2$ pulse acts on it concurrently. This effect is described by photochemical reaction (see the bottom line in Fig.8). Note that acting separately, neither factor leads to destruction of the coupling element.

That way, illumination of the whole structure with modulated light allows us to record this sequence due to destruction of the ferment-transformer at points where the running chemical pulse and light pulse coincide (this effect is represented by two plots at the bottom of Fig.8). The recorded information can be read with the chemical wave that in propagating down the structure will give rise to electric signals at the moments of contact with intact molecules of ferment-transformer.

However, the diffusion of hydrogen ions causes the reaction to propagate further, producing a running chemical pulse in the form of hydrogen peroxide concentration wave.
We have given this example for the reader to evaluate the intricacy of the processes that go on in the brain of a living being.

It is important to note that the main peculiarity of optobiochemical memory is a self-addressing process.

Conclusion

The problem of the development of artificial elements that can affect the neural network (or network elements) and thus enhance the abilities of the human brain requires deep understanding of neural-net memory operation. Today we are still a long way from this.

Nevertheless, we can consider the simplest ways of solving the problem now. One of the ways we offer involves "bioelectronics' interface", i.e. a special electronic device that can be implanted in the brain and incite a biologic neuron (or a group of neurons) or receive signals from biologically excited neurons from a particular "memory cluster". It should be noticed that the neuron's ability to interact with electronic devices have been confirmed experimentally. The simple illustration of this fact is given in Fig. 9 borrowed from [8].

Fig. 9. Principle of bioelectronics interface. a) Recording of membrane potential of the neuron by transistor. b) Capacitive stimulation of the neuron by silicon chip.

More complex ways of enhancing the memory capacities of the brain (including the use of external interfaces and multiple-element neural structures [2,7]) need deep understanding of the phenomena that go on in the neural system of the brain when it is affected by electromagnetic, ultrasonic, magnetic, electric, etc. fields.
The research is supported by the Russian Foundation for Basic Research (grant 02-01-00457) and Scientific School.

References


4 Presently Institute of Optical Neural Technologies of Russian Academy of Sciences