

E. N. Sokolov's Neural Model of Stimuli as Neuro-cybernetic Approach to Anticipatory Perception

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Abstract. We present the original ideas of E. N. Sokolov on the “neural model of stimuli”, the functional organization of orienting reflex, formation of neural memory, neural approach of the reflex arc as presynaptic associative learning, post-tetanic potentiation and reflection on the genome of the neuron membrane, corresponds to model based anticipation historically are presented. The influence of innovative ideas to the development of scientific investigations of active anticipatory systems, closed-loop coding-decoding control, the visual perception as analysis by synthesis and other scientific approaches in the Lithuania are given.

Keywords: anticipation, detectors identity and novelty, neural model, neuro-cybernetic, orienting reflex, perception, post-tetanic potentiation, reflex arc

1 Introduction

Evgeny N. Sokolov is the modern successor of the studies on Pavlov's Conditional Reflex in the Soviet Union postwar period, when psychophysiological phenomena began to be investigated by neuro-cybernetic models. Although the concept of anticipation was not common in Russian science, problems of predictive systems in cybernetics, predictive (active) actions in physiology and psychology, and particularly the original idea of E.N. Sokolov on the “neural model of stimuli” as a development of the orienting reflex theory in fact correspond to model based anticipation. His innovative research approach influenced the scientific investigations of other Soviet republics, particularly the development of scientific ideas in Lithuania.

Exhaustive recent presentations of E.N. Sokolov's scientific concepts are given in the book “*The Orienting Response in Information Processing*” (2013) [1] and the textbook “*Physiology of Higher Nervous Activity*” (2005) [10]. The present paper reflects only selected scientific positions of Sokolov's work, as it influenced the formation of scientific concepts of present authors and research problems of the Biophysics-Neurocybernetics laboratory of Vilnius University in the terms and ideas of model based anticipation.



Evgeny N. Sokolov (1920 - 2008)

As mentioned, Sokolov's idea of the “neural model of stimuli” as a development of the orienting reflex theory in fact corresponds to concepts of model based anticipation. At the same time, Sokolov's approach to the “neural model of stimuli” arose before Robert Rosen's book “*Anticipatory systems*” appeared in 1985. Sokolov's monograph “*Perception and Conditional Reflex*” was published in Russian already in 1958 [2], and it was

translated to English in 1963 [4]. In 1960, Sokolov's original paper "Neuronal Models in the Orienting Reflex" was also published in the U.S. [3].

E.N. Sokolov drew attention to one of the most important reactions of human beings – the response to stimulus novelty in the form of an orienting reflex, or a "What's that?" reflex as Ivan P. Pavlov called it. Studies of the dynamics of the orienting reflex in humans and animals have shown that the orienting response does not occur to a stimulus as such, but only as a result of comparing the stimulus with traces left in the nervous system by some preceding stimuli. This led to problems regarding the functional organization of the orienting reflex, the formation of stimulus memory, neural approach to the reflex arc in terms of presynaptic associative learning, post-tetanic potentiation, and the reflection of the neuronal membrane on the genome.

2 Sokolov's Way from Pavlov's Conditional Reflex to Neural Model Based Anticipation

The orienting reflex is a complex response of animals and humans to the novelty of a stimulus. The biological meaning of the orienting reflex is to create better conditions for stimulus perception. This is achieved by forming a complex of somatic and autonomic responses, and changes in the level of activation of the central nervous system in general associated with an interruption of the current activity of the organism. A schematized structure of the orienting reflex in the general conditional reflex system as conceived by Sokolov is shown in Fig. 1

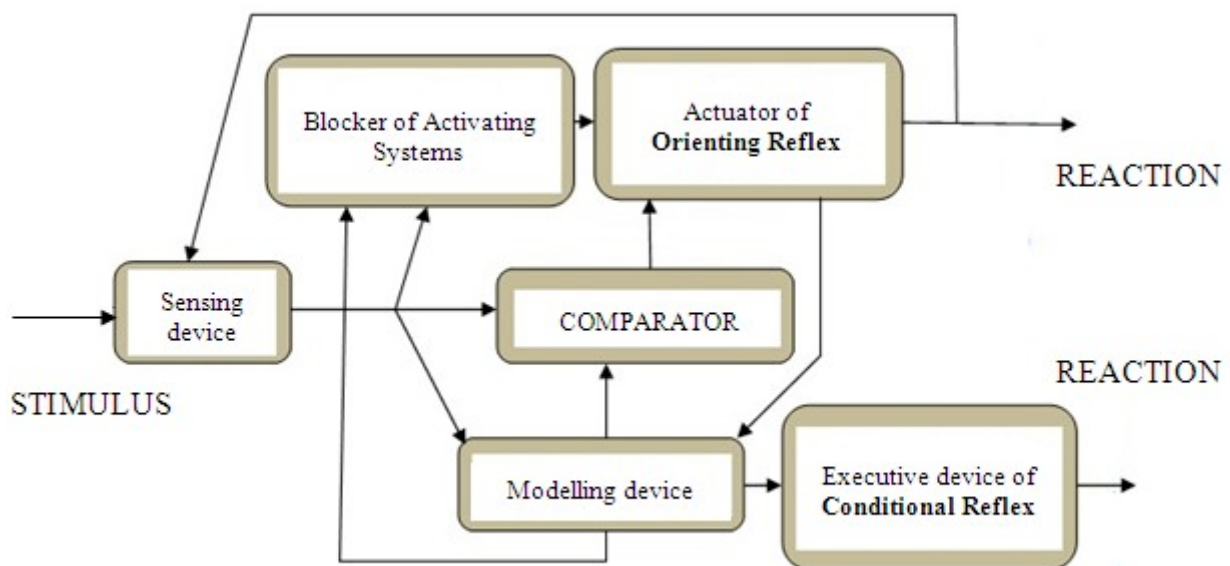


Fig. 1. Schematized structure of the functional organization of the orienting reflex constructed as the general conditional reflex system (following Sokolov's representations, 1963, 1975).

There are three main groups of components constituting the orienting reflex: 1) motor; 2) vegetative; and 3) changes in the level of activation of the central nervous system. The motor components of the orienting reflex include: 1) The reaction of eye-movements in the direction of the stimulus, sniffing; 2) the reactions ensuring the maintenance of posture and approaching the stimulus. The vegetative components of the orienting reflex include vascular responses in the form of head and limb vasoconstriction and vasodilatation, providing an increase in blood supply to the brain, skin-galvanic response (GSR), changes in heart rate and breathing. Besides stimulus novelty, the orienting reflex depends on other factors and properties such as stimulus change, stimulus complexity, and ambiguity. The orienting reflex occurs in case the stimulus and the traces left by previous stimuli (the neural model of stimulus) do not coincide. Together with the repetition of the new stimulus causing the orienting reflex, the reflex attenuates. Depending on the extent of the spread of excitation in the nervous system a distinction is made between local and generalized forms of the orienting reflex. In the process of extinction, the generalized orienting reflex is replaced by a local, physical tonic orienting reflex. For understanding the orienting reflex in terms of anticipation, special attention must be given to the significance of the comparator device (Fig. 1) and especially to the organization of the modelling and memory structures.

2.1 Formation of stimulus memory. Bringing perception and memory into theories of habituation is appropriate in discussing the reactions to novel or familiar stimuli by intact mammals. The main theory follows from Sokolov (1963, 1975), which analyzes “the formation of a neuronal model of the stimulus” to describe the processes of categorization and memory formation which result from repeated experiences of an external event. The essence of Sokolov’s theory of habituation and neural correlates of memory formation are given in Fig. 2.

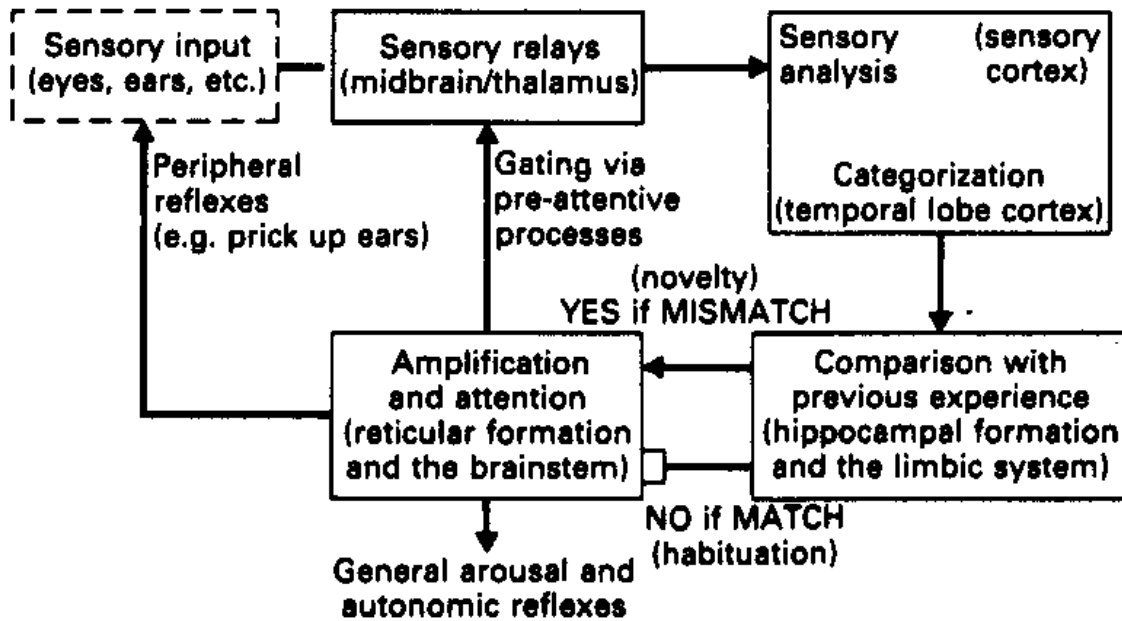


Fig. 2. Sokolov’s scheme of habituation (Sokolov, 1963-75)

The function of the neuronal model is to distinguish novel from familiar stimuli, and also unexpected and surprising events from expected and therefore insignificant ones (this is an additional function, since familiar or well-known stimuli may be surprising if they occur at an unexpected time or place). It is supposed in Sokolov’s theory that there is an active process of comparison between an incoming stimulus and the established neuronal model: if there is a match between the two, the incoming stimulus can be ignored.

Given a comparator mechanism, any response originally displayed to a stimulus – such as the withdrawal of a snail’s horns for example – may be suspended when the stimulus has become familiar and matches expectations. However, in Sokolov’s theory, emphasis is given to the physiological reactions in human subjects that are measurable and correlated to some degree with the attention and arousal generated by incoming stimuli. Such responses are selected partly for convenience, and partly because they appear to be useful indicators of stimulus novelty. They include, understandably, the turning of the head and eyes towards the source of a localized stimulus, and the desynchronization of the electroencephalograph (EEG) which is known to occur with subjective attention to external stimuli in normal human adults. Slightly less obviously, responses which are in practice correlated with stimulus novelty include the dilation of blood vessels in the head and the “galvanic skin response“ (GSR), which is a drop in the electrical resistance of the skin and usually measured on the hand. In the theory, these signs are taken to be indications of the activity of the amplifying systems in Fig. 2.

Other innovative methodological tool of Sokolov was to interpret the functional organization of single neuron components and their networks [5-9]. This involved analyzing multi-stage and hierarchically organized perceptual systems at the synapses of an individual neuron in the frog spinal cord or in the abdominal ganglia of Aplysia. In mammals there is ample evidence that the anatomical basis of attention includes the reticular activating systems and reactions of the hippocampal neuronal system of the brain (Fig. 3., Sokolov, 1963, 1970).

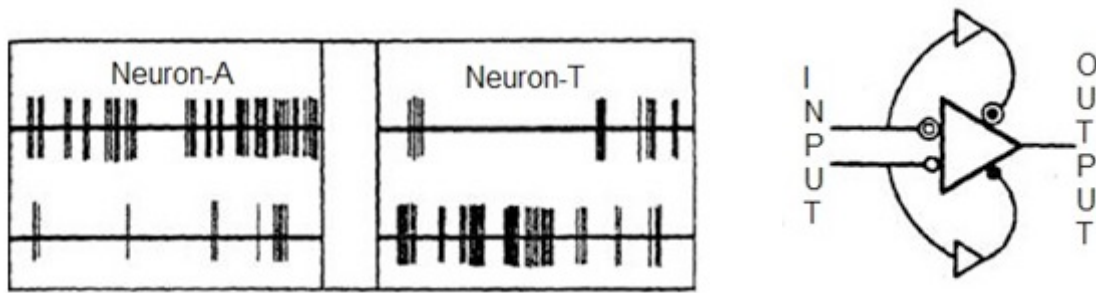


Fig. 3. Left: extinction reactions of hippocampal neurons corresponding to excitation (A-type) and inhibition (T-type) to stimuli. Right: a diagram of a neural network that provides selective "addiction" to the stimulus (E. N. Sokolov, 1970)

Especially in the short term, increased familiarity with stimuli means that they are ignored. However, exposure to a stimulus on its first instance will elicit increased attention to it, and according to the above, familiarity with a stimulus implies that the perceiver possesses a neuronal model or memory of it that registers not only the elementary, but also the complex properties of the signal which include temporal relationships (Sokolov, 1975). Thus, the existence of a preformed neuronal model may improve perceptual performance if an already familiar stimulus acquires new significance – for instance, by a change in context, or by changes in internal or external motivational factors. That is the formation of a stimulus memory. The next step in the understanding of anticipatory conditional and orienting reflex reactions is based on the approach to the reflex arc as a layered neural structure.

The neural approach to the reflex arc is represented on Fig. 4. Based on the analysis of specific mechanisms of various behavioral acts, E.N. Sokolov developed a general principle of the functional organization of the reflex arc – presented in the form of a conceptual scheme of the reflex arc by neuronal interpretations.

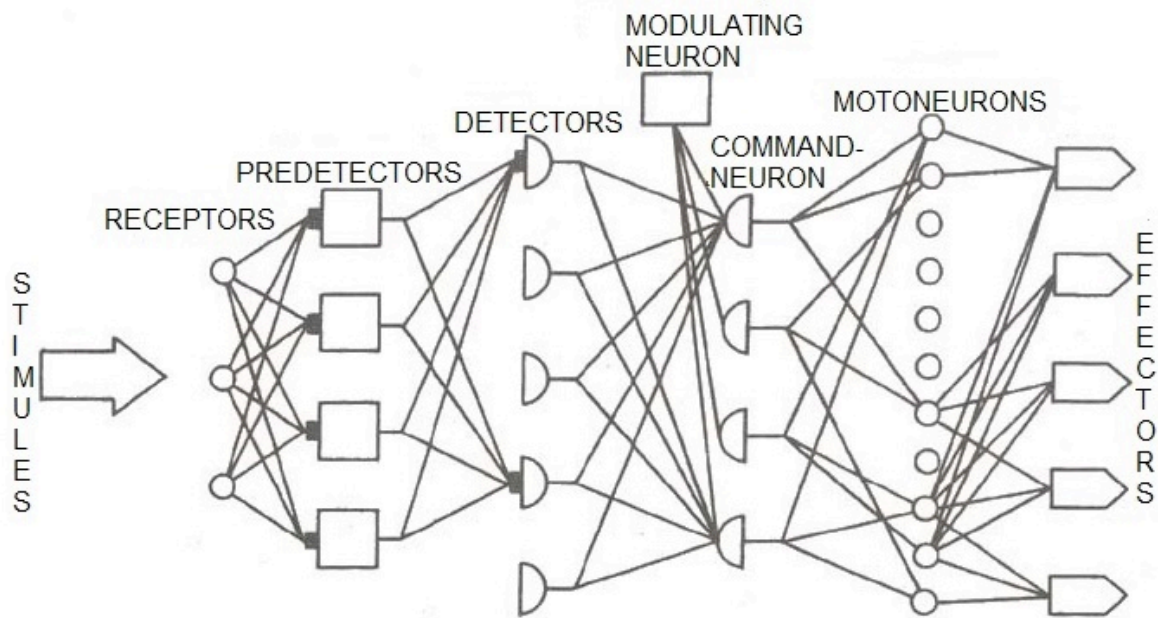


Fig. 4. The conceptual organization of the reflex arc neurons located at the entrance of the touch analyzer (E.N. Sokolov, Ch.A. Izmaylov, 1983).

In the conceptual scheme of E.N. Sokolov and Ch.A. Izmaylov, the proposed neuronal organization of the reflex arc contains three interrelated but relatively autonomously operating systems of neurons: an afferent (sensory analyzer), effector (executive – organs of locomotion), and a modulating one (controls communication between the afferent and effector systems). The afferent system, starting with the receptors, is composed of predetector neurons producing common preprocessing of information available to the senses, and of the detector neurons emitting only certain kind of incentives that are selectively configured, thereby only reacting to certain stimuli. The effector system includes command neurons, motor neurons, and effectors, i.e. nerve cells. This system

generates commands from the center to the periphery of the body and is responsible for their execution. The modulating system comprises nerve cells associated with the processing of information that circulates between the neural networks that make up the afferent and effector subsystems of the conceptual reflex arc.

The reflex arc activity can be represented as follows: receptors are specific sensory devices that can perceive and react to certain physical impacts of stimuli as signals. Receptors are in turn associated with selective detectors – neurons selectively responding to certain stimuli – and this connection can be either direct or, as shown, mediated by the predetectors. Selective detectors operate by the following principle: a specific combination of excitation corresponds to the maximum excitation of receptors in selective detector neurons. Further, signals from the detectors are transmitted to command neurons. The excitation level of command neurons is regulated by the activity of modulating neurons. From command neurons excitation travels to motor neurons associated with movement and other bodily effectors.

In the work of the conceptual reflex arc a feedback mechanism is included (not present in Fig. 4. to simplify the block diagram, but shown in other figures). Through the feedback mechanism, the excitability of receptors and effector neurons is regulated. Allocation of the basic elements of the conceptual arc was the result of summarizing the neural mechanisms of reflexes in animals at different stages of the evolutionary ladder. A neuron determines its reflexogenic area and population of motor neurons that make up the target synapse at a command neuron that determines the motor program.

The spike activity of command neuron excites a pool of related motoneurons and invokes the local reflex fragment. Modulatory neurons constitute a special class of elements in the structure of the reflex arc. They receive signals from the external environment and internal organs, but their function is to regulate the tone of reflex activity of the brain. Special mechanisms for regulating the excitability of neurons consist of the modulating (activating and inactivating) system with generalized brain-wide effects and local (selective) points of impact on the system responsible for the implementation of a new reflex. Modulatory effects are implemented mainly through a change of excitability in command neurons that ultimately leads to the displacement of the maximum excitation from one system of command neurons to another, resulting in a redistribution of priority and reactions.

Neuronal "detectors" of novelty (H. Jasper) and identity marked a particular interest of Sokolov as important elements of attention that respond to the first stimulus presentation [9]. Novelty neurons are used to distinguish new signals. As their distinct feature, their background impulses increase under the influence of new stimuli of different modalities. These neurons are connected through multiple links to separate detector areas of the cerebral cortex. Synaptic plasticity of excitatory neurons is related to stimulus novelty. By repeating the stimulus and its duration, the strength of the excitation response of the novelty neurons can be selectively inhibited, so that their further activation disappears and is stored only as background activity.

The identity neuron also exhibits background activity. These neurons act through plastic synapses with detectors from different modalities. But unlike novelty neurons, these neurons communicate with sensory detectors through inhibitory synapses. Under the action of a new stimulus, the background activity of identity neurons is suppressed; in contrast, it is augmented by the action of usual stimuli.

Thus, new stimuli excite novelty neurons and inhibit identity neurons. In other words, new stimuli excite the activating system of the brain related to new stimuli, and suppress the synchronization system. Familiar stimuli act just the opposite – they increase the activity of the blocking system and do not stimulate the activating one.

Behavioral acts are realized through the orderly organization of the reflex arc, in which nerve cells perform the coding of signals. In the conceptual model of the reflex arc, E.N. Sokolov considered the principle of (stimulus-response) encoding by channel number as a universal principle of the central nervous system of animals at different levels of phylogeny. Analysis and delivery of sensory information to the system of command neurons in higher animals is carried out by sensory neurons with a hierarchical principle of detector properties. The cerebral cortex formed by a plurality of detectors is a system analyzer. It combines sensory neurons into functional modules (micro-, macro-, and hypercolumns), incorporated into the three-dimensional structure of the brain as a multidimensional system of local sign analyzers (hypercolumns). As a result, the processing of sensory information is carried out on the basis of coding by channel number in a variety of parallel sensory channels active at the same time.

Sokolov's interest in understanding the neuro-reflex mechanisms next brought him to neuro-synaptic contacts and molecular-genetic mechanisms. A general scheme of the functional organization of presynaptic associative learning, post-tetanic potentiation, and reflection of the neuronal membrane on the genome is presented in Fig. 5.

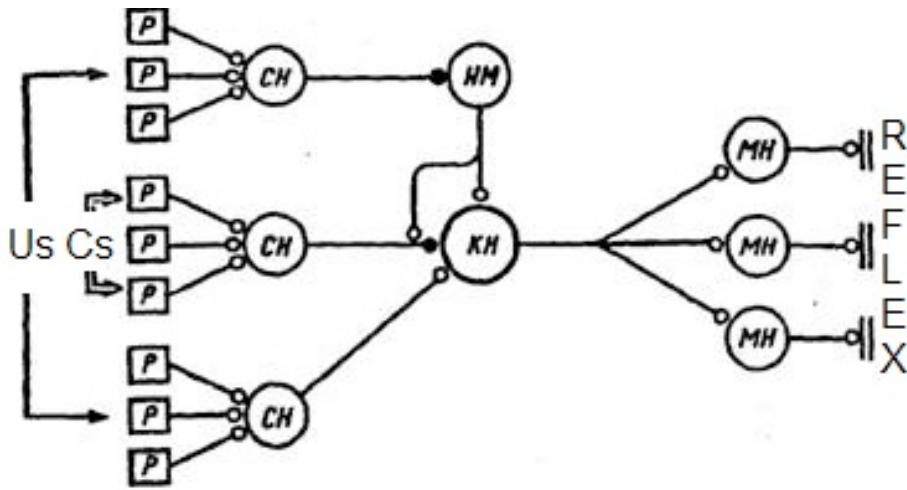


Fig. 5. Scheme of the development presynaptic associative learning in the arc of a passive-defensive behavior. CS - conditioned stimulus BS - unconditioned stimulus , P - receptors , CH - sensory neurons , NM - modulating neuron KH - command neuron , MN - motoneurons , p - reflex ; black circle - plastic synapse, light – nonplastic synapse (T.N.Grechenko, E.N.Sokolov,1987)

Formation of reflex-based plastic synapses of neurons is under the influence of a neuro-modulator allocated humorally or synaptically. Serotonergic neurons have been found, the stimulation of which causes an increase in EPSP command (motor) neurons implementing the reflex. These neurons facilitate synaptic response to the conditioned stimulus, often called "reinforcing" or modulating one. Thus, it is assumed that the conditioned stimulus causes EPSP and the unconditioned stimulus neuron affects through modulator the efficiency of conditioned synaptic inputs. Associative specificity is due to the fact that neuromodulation selectively enhances presynaptic mechanisms of functionally active target cells.

Two control loops exist: a short-term (mediator $> Ca^{2+}$ -proteinkinaz \rightarrow inactivation of potassium channel) and a long one (mediator $> Ca^{2+}$ \rightarrow protein controller \rightarrow kernel \rightarrow mRNA \rightarrow synthesis of protein kinase \rightarrow strengthening the blockade of potassium channels), highlight phosphorylation of histones and other chromatin regulatory proteins, i.e. proteins - regulators of the genome of the neuron. This process completes the synthesis of a number of neurospecific proteins (Fig. 6.).

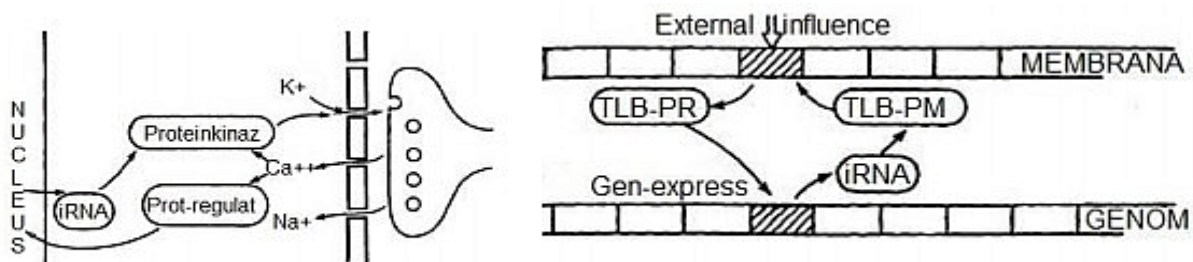


Fig. 6. Schemes of post-tetanic potentiation and hypothetical approach to the reflection of the neuronal membrane on the genome (T.N. Grechenko, E.N. Sokolov, 1987). TLB - translocation protein, PR - protein regulator , PM - protein modulator, iRNA - information ribonucleic acid.

Processes leading to a change of state of the neuronal membrane are deployed within 10-20 ms after impulses. This effect is caused by the usual action of the neurotransmitter, and possibly part of neuropeptides and satellites, the impact of which is relatively short (mediated "second messengers", and possibly direct) effect on the affinity of the receptors of the postsynaptic membrane. Effectiveness of the synapse may be associated with long-term changes causing selective gene expression (Fig. 6.) and their transcription with the participation of mRNA. Synthesized enzyme (protein modulator) is transported to the protein portion of the cell membrane, which has been encoded "marker" protein.

This scheme assumes that the expression of genes, once induced, is then continuously kept, providing the maintenance level of protein synthesis, governing receptors involved neurotransmitter active synapses (Fig. 6). By this scheme, the transition from addiction to the development of the memory trace occurs on pre-and postsynaptic mechanism (Fig. 5).

In case of developing a new skill, reflex should start acting through different combinations of synapses and neurotransmitters. This change operates through another protein modulator which sets the corresponding receptor protein in a reactive state, and it may take long to take over specific mediator. On presynaptic calcium levels, activating protein kinase closes potassium channels and thereby enhances calcium intake and the release of neurotransmitters into the synaptic cleft. On activation of postsynaptic level to sodium channel joins the entry of calcium, including protein and disabling potassium channels, increases neuronal excitability. With the participation of the neuron genome amplified protein synthesis modulators affecting the efficiency of protein kinases that regulate the closing of potassium channels.

All these numerous ideas of Sokolov were received by his Lithuanian students and adopted and developed by them at the University of Vilnius between 1962-1990 and later years.

3 Development of E. N. Sokolov's Ideas on Anticipation in Lithuania

Sokolov's scientific concept of active anticipatory systems of perception has been developed in Vilnius University as active analysis by synthesis (A-by-S) of cognitive perception and the more general anticipatory closed-loop coding-decoding (CL-CD) control approach. The functional organization of an anticipatory system of active perception is presented in Fig. 7. [11-16].

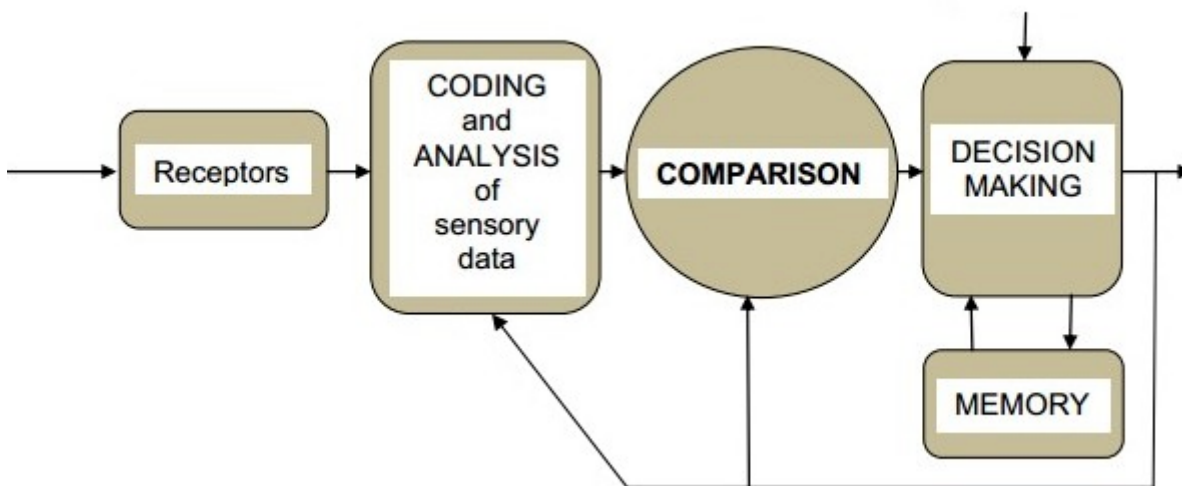


Fig. 7. Functional structure of active pattern recognition systems (V. Vanagas, 1991).

The main difference between passive (perceptronic) and active perception systems is the existence in the active system of feedback links from the decision-making act to comparison and analysis. Due to the presence of feedback links from the decision-making to the analysis the system is able to make a selective choice of information entering the comparison procedures. Because of the links between procedures it is possible for the system to analyse a complex visual scene into parts. Due to feedback links with the comparison, a possibility emerges in the system: (i) to check the correctness of the decision, i.e, whether the output of the system corresponds to the input image; (ii) to change decisions in the case of need till inadequacies disappear. It is natural to presume that the act of decision does not generate hypotheses accidentally, otherwise the recognition of even simple images would take a lot of time. The system gets considerable information on the possible contents of hypotheses from the results of the comparison of implied and real images. Yet, other sources of information must be used by the system for the generation of hypotheses. A preliminary analysis of the image or a part of it may make up one source of such information, e.g., by using a scheme as in passive perceptive systems. Other reasons restricting the amount of possible expectations lie in the motivational influences of an organism, and in the awareness of the whole recognized situation both in space and in time. Tachistoscopic experiments with 4 subjects

(12 repetitions with each of them) revealed that the period of the hypothesis-testing cycle is 8 – 10 msec (with SE 1.0 msec.) in the human visual analyzer (V. Vanagas, O. Balkelytė, D. Kirvelis et al., 1973).

Active anticipatory Homunculus of vision in the brain. Hypothetical *homunculus* of vision neuro-design architecture and functional organization scheme as analysis by synthesis (A-by-S) perceptive neuro-system are presented in Fig. 8. [13-16]

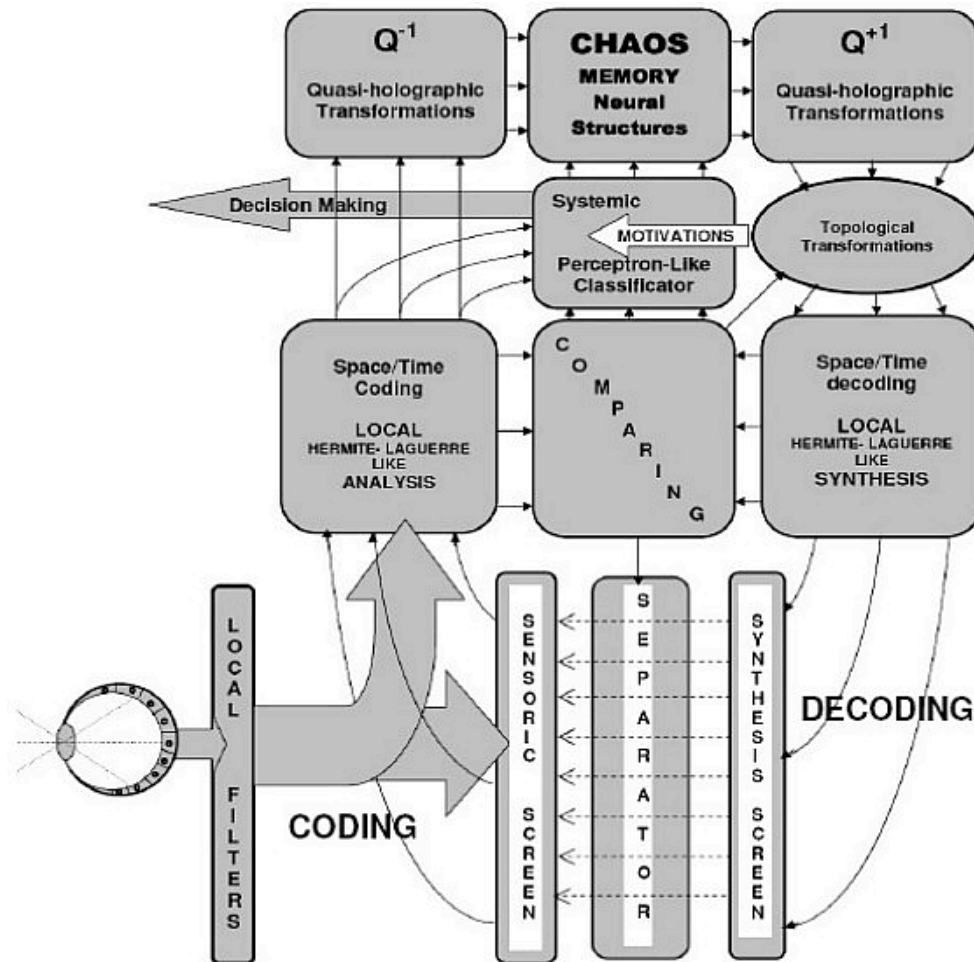


Fig. 8. Active anticipatory *Homunculus* of vision in the brain (D. Kirvelis, 2013)

The functioning of visual *homunculus* as active analyzer consists of following intertwined operations: analysis of visual scenes projected onto SS; quasi-holographic “tracing” of images; preliminary recognition; quasi-holographic image reconstruction from memory onto RS; comparison of images projected onto SS with images reconstructed onto RS; and correction of preliminary recognition. The CL-CD procedure of analysis-by-synthesis corresponds to visual procedures on mental images. It is supposed that the image “tracing” and reverse image reconstruction are based on quasiholographic, CHAOS principles of brain neuronal organization and are periodic CL-CD procedures.

It is proposed that the neuronal structure implementing the quasi-holographic analysis-by-synthesis ought to possess at least ten functional layered complexes: the receptor layer where the retinal image is projected; layer of local filtering; local Hermite-Laguerre like analyzer and local Hermite-Laguerre like synthesizer with comparator between them. These structures are looped by quasi-holographic memory layered complexes Q^{-1} and Q^{+1} with CHAOS memory neural structure controlled by systemic perceptron-like classificatory in-between them. The memory traces are extracted by means of the topological transformations structure controlled by signals from the comparator.

But from general position of the functional organization anticipatory systems as an essential part of the idea is the concept of closed-loop coding-decoding control (CL-CDC). The **Closed-Loop Coding-Decoding concept as the base of anticipatory control** is presented in Fig. 9. [17-19].

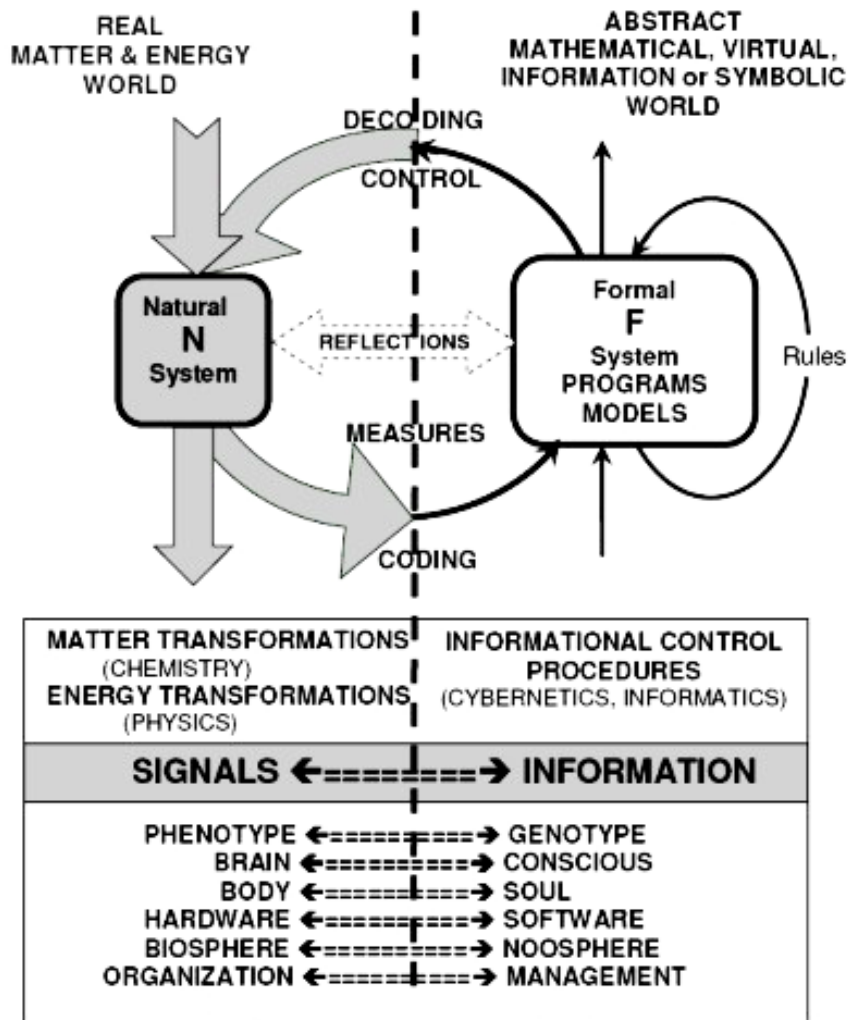


Fig. 9. The paradigmic scheme of the converged matter-energy and information technologies or organizationally closed, matter-energy and information open by closed-loop coding-decoding (CL-CD) principle organized anticipatory control system (Kirvelis, 2002).

According to the CL-CD scheme, the natural system **M** of the real world sphere may be represented by encoding (coding) procedure on the formal (abstract, mathematical, virtual, computer) world sphere **Info** as a model of **M**. Model or formal system **Info** operates with special rules. The coding procedure corresponds to observations, measurements, analysis, representations or reflections. Accordingly, the decoding procedure is de-reflection or synthesis of the natural system **M** under control of a model programmed in the formal system **Info**. The decoding accompanies procedures of interpretation, control, prediction, synthesis and anticipation. Here, it is necessary to mention that there are two classes of models. Thus, encoding of the system **M** can produce two kinds of models: (a) *gnostic model* **Info_G** (intended for cognition of **N**) and (b) *action model* **Info_A** (intended for reproduction of **M** or production of changes in existing **M**). In some systems, the models **Info_G** can be transformed to **Info_A**, and in some systems, the model **Info_A** is produced directly.

Coding (encoding) should be understood as a reflection of a real system (nature or a technological process) in an abstract virtual form on *memory* structures (DNA, hormones, neural networks, programs, books, etc.) in a way that decoding from the abstract form to the real one (and purposive actions in a real system) would be possible.

The coded reflection in the memory is a *gnostic model* or a technological project (*action model*) of the real system. This action model or a coded representation for control is the essence of information. Decoding is the realization of such a project or the control of biotechnological procedures according to information. In the process of decoding, the activated coded states of the memory structures or the projects for synthesis of reality are reflected in the dynamic states of the real world, real structures of body, etc. The real world is changed according to the action model.

The full closed-loop coding-decoding system consists of complex, partially autonomic, organized systems. There are genetic, hormonal, neural, psychical, social, robotic organized systems in the world. Dualistic material↔informational mapping manifests itself in the following organized systems: signal↔information;

phenotype↔genotype; body↔soul; brain↔thought; hardware↔software; biosphere↔noosphere; social group↔management; state↔government.

The systems that function according these principles are organizationally closed and informational open. Organizational closeness causes the functional compatibility of coding-decoding and functional sense (semantics) of coded reflections. Informational openness means ability to join additional information about environment to the pool of the existing world models (the pool of gnostic and action models). This openness also means the feature of gnostic models to change according to changes of the real world. Later, these changes are transferred to the action models. These related changes of real world↔gnostic models↔action models means “informational metabolism”, in analogy with mater and energy conversion.

It is undoubtful that most elaborated active anticipatory CL-CD control systems are a part of functional structure of biological organisms, because they are the result of natural evolution that developed these technologies during millions years of life history.

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