Development of Anticipatory Control in Bio-Systems: Five Levels of Closed-Loop Coding-Decoding in the Visual Analyzers

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Abstract
Evolutionary analysis of functional organization of nerve systems and of behavior shows five informational control levels (reflexic L.; multireflexic coordination L.; regulative L.; perceptronic analyzing L.; Analysis-by-Synthesis L.) that represent specific procedures of the closed-loop coding-decoding. Maybe weak anticipative prediction is realized at simple reflection and multireflexic coordination structures, incursive anticipative feedback control - at regulation and simple analyzers structures, and strong anticipation - at neocortex structures that work by Analysis-by-Synthesis. The strong anticipation maybe is used only in brains of mammals and birds that are able to create models of future activities that means ability to think. Higher mammals especially apes and humans have sensory screens that enhance mental imaging in *Area Striata* zone.
Keywords: anticipatory control, information, organized system, coding-decoding, closed-loop

1 Introduction

The Earth's life evolution is the most marvelous example of sophistication and improvement of organized complex systems. Biosphere evolution is analyzed from many positions, but one of most prospective analysis positions is a cybernetic one.

Organism is organized control system so its behavior tends to be functionally purposeful and goal-directed. (Powers, 1973; Turchin, 1977; Rosen, 1985, 1991; Rocha, 1996; Joslyn, 1997, 1999, 2001; Cariani, 2001). Organism as every organized system consists of two closely connected qualitatively different subsystems – *controlling subsystem* and *controlled subsystem* (Kirvelis, 1998, 2000). Here rolling subsystem through informational input to controlled subsystem determines the behavior of it and of all organized system. This informational input generated on basis of forecasting and anticipation, i.e. controlling subsystem generates decision earlier than executive organs begin to act in response to incoming commands. Anticipatory control or model-based control in the biosystems was described by R. Rosen at 1985 and emphasized by D. Dubois at 1997. But today anticipatory control is not well understood yet and needs for additional experimental and theoretical studies.

So better understanding of anticipatory control can be achieved in studies of functioning principles of nervous systems. The best object of research here is the visual analyzer because it is the best studied part of central nervous systems today.

2 Organized System, Control and Anticipation

Quintessence of anticipatory control is represented in Fig.1. as funtional feature of the organized system (Kirvelis, 2000). Controlling subsystem of organized system has two *receptoric subsubsystems* (RSSS). *External receptoric subsubsystem* (ERSSS) collects information about external environment **U**, and *internal receptoric subsubsystem* (IRSSS) collects information about internal environment (about internal state of organized system and actions **X** of organized system).

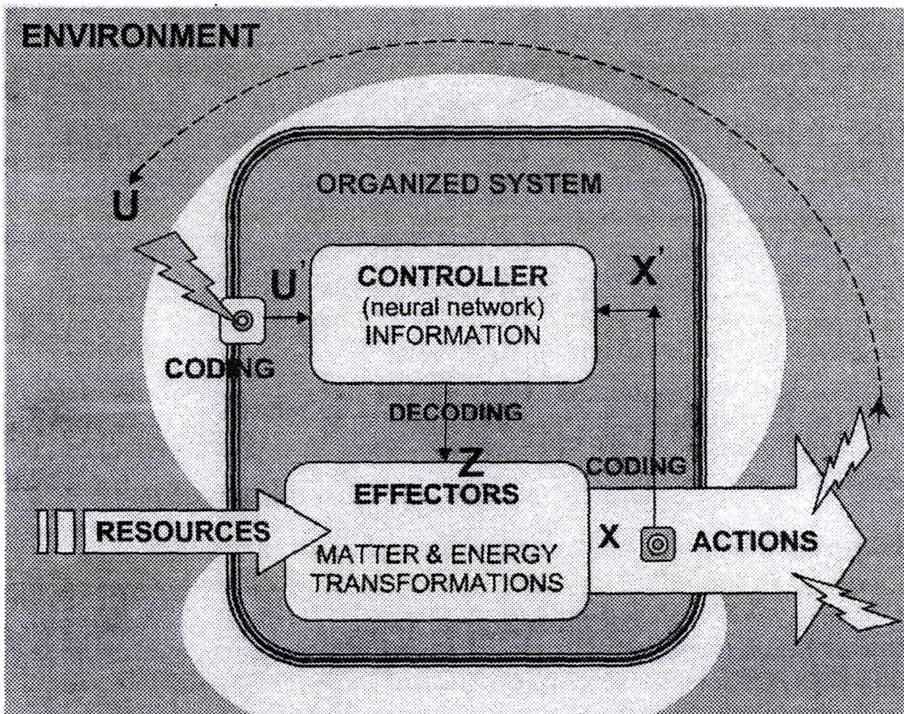

Figure 1: Functional structure of the organized system with combined feedforward and feedback informational control by neural networks or external and internal closed-loop coding-decoding. (Explanations in text)

Both receptoric subsubsystems do primary encoding procedures and transfer information to main controlling subsystem. Controlling subsystem can be with memory or without it. Memory is necessary for generation of models of external and/or internal environment. Increase of memory defines ability to form more complex models where information about past is used. In some cases more complex models can be more adequate and can define better anticipation and correspondingly better anticipatory control.

In studies of consciousness-able animals (humans mainly) and organized systems of conscious individuals may be necessary to individuate third information collecting system characteristic to conscious persons. According Beitas hypothesis (Beitas, 2001) on consciousness as interpersonal interface, the consciousness-as-mechanism is a system (a subsubsystem here) that selects information for transfer to other individuals from the same social group. The primary destination of this selected information is to increase social group survival through better survival of individuals. In context of this hypothesis the consciousness-as-mechanism can be interpreted as *metasensory system*. The one of differences of this system from sensory systems is that it supposedly does not have the receptors. So here this system can be named as *consciousness subsubsystem* (CSSS).

There are two closed-loop coding-decoding procedures in organized systems at least (Kirvelis, 2002). The first one (classic) is based on internal feedback, and a second one is based on external feedback through system impact on external environment and information about external environment got from externals receptors (ERSSS). The last closed-loop coding-decoding structure is named *Umwelt* in biosemiotics and gets a special attention (Uexkull, 1926; Rocha, 1996; Kull, 1999; Sharov, 1998).

All named anticipatory control systems exist in evolution of animal visual analyzers. They are found mammalian and human visual analyzers where they act parallelly and complementary. In lower animalsthe highest named structure mayby aren't developed because evolution of visual analyzer has stopped at lower level.

3 Functional Organization of Neuronal Structures and Animal Behavior

The interrelation of animal behavior and functional organization of nervous system are old news. It is best seen in phylogenetic analysis of nervous systems. The R.de Cajal (1911) [Favareau, 2002] named 4 levels of functional organization:

- most primitive organization - every cell is photoreceptor and motoric effector at the same time (A)
- primitive organization - photoreceptors (r) are specialized cells that directly synaptically control motoric effectors *m* (B) ;
- higher organization interneurons *g* generates commands to motoric effectors (C);
- the most high level - the horizontally and vertically extended system of interneurons coordinates the motoric behavior of organism (D).

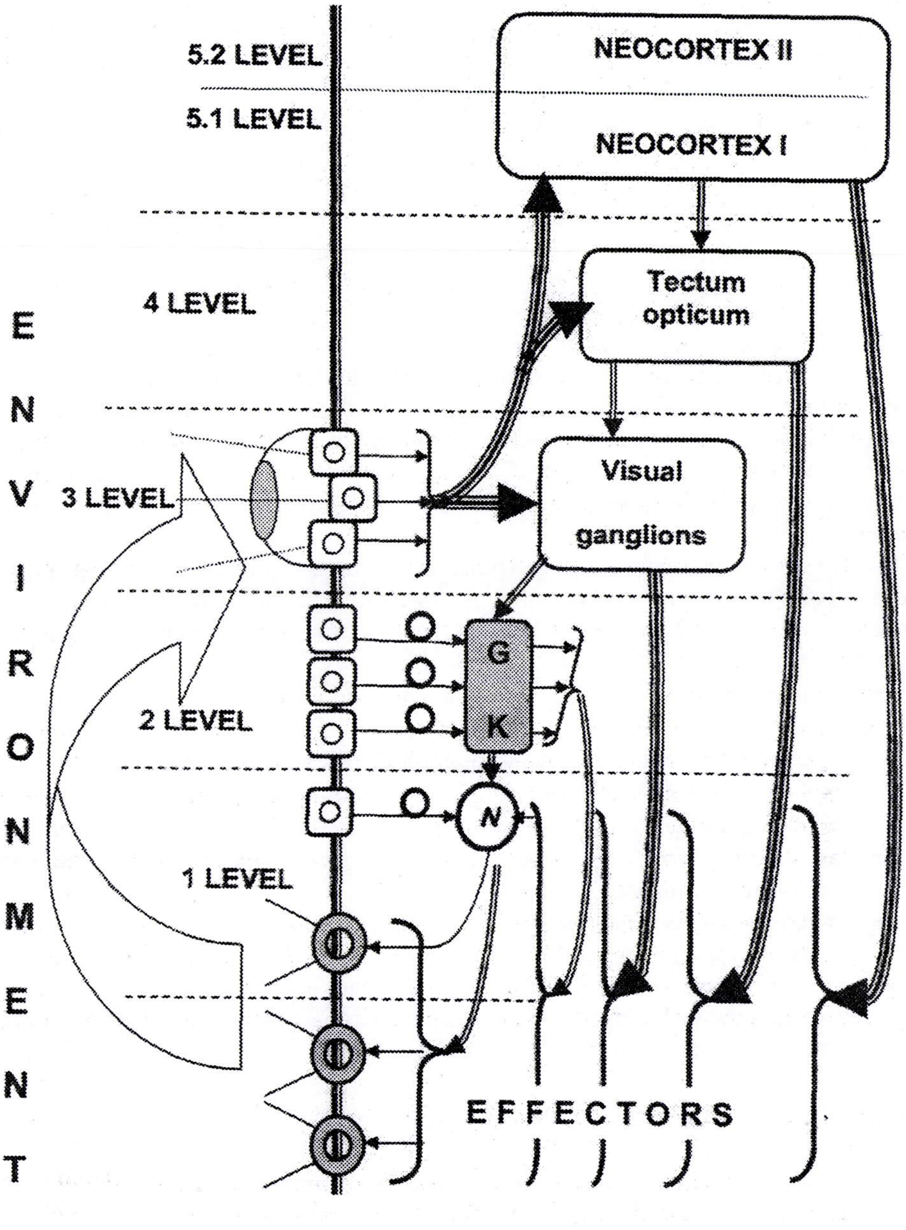

Figure 2: Five neurofunctional levels of the closed-loop coding-decoding in the animal visual analyzers. GK- the ganglions of the coordination. (After N.A.Bernstein, 1967)

Neuromorphologist G. Poliakov (1965) reviewed the neural evolution from the neurocybernetic position of functional purport. On the basis of neurophysiological studies of motoric system by N. Bernshtein (1947) and of neuromorphological studies of human nervous system embryogenesis by V. His, G. Zhukovskaya, and T. Leontovich he divided neural structures of neural analyzers to 4 ascending levels (Fig.2.):

1. Reflexic (classic reflex arc) level (corresponds to B level of R.y Cajal;
2. Coordination level where structure implement chain or cycle of traditional reflex arcs (corresponds to D level of R.y Cajal);
3. Analyser – coordinative level, where coordination level is augmented by neurostructures of cerebellum;
4. Thalamus analyzer level.
5. Neocortex analyzer level that is true analyzer level according I .Pavlov.

The neurostructures of fifth (neocortex) level are found in warm-blooded animals, especially in mammals. They can have (I.S. Beritashvili, 1974) well developed layer of stellate neurons with intertwined axons in *Area Striata* (neocortex II, diurnal monkeys and humans) or little developed layer (neocortex I, mammals with brain of lower organization).

This system of neural structures organization levels is compatible with ethological research. From this point of view the phylogenetic diagram of V.G. Dethier and E. Stellar (1961) on contribution of behavior components to all behavioris interesting.

It can be expected that:

- protozoans behavior is based only on taxes and tropisms;
- behavior of primitive multicellular invertenbrates consists of taxes and tropisms augmented by unconditional reflexes (some of them has instincts);
- behavior of some arthropods and cephalopods is dominated by instincts and learning through conditional reflexes;
- all 4 named forms are characteristic to lower vertebrates (fishes, amphibians and some reptilians);
- behavior of mammals and birds is improved by thinking (a fifth level of behavior mechanism). The thinking is most expressed in human behavior.

Supposedly all these behavior forms are related to evolutionary development of special neurostructures and correlate with emergence of new principles in informational control.

4 Evolutionary Levels of Visual Analyzer

Here the functional organization of neural systems of some organisms and their visual analyzers are reviewed from the position described in above.

4.1 Reflexic Visual Analyzer

Representative of organisms with most simple phototaxic vision system is *Euglena* (Diehn, 1973). The functional scheme is in Fig. 3.

Euglena is an unicellular organism without neural system, but functional qualities of her behavior exactly correspond to most primitive level of visual analyzer. Euglena's stigma works as photoreceptor. Flagellum is an effectors that is energized by ATP molecules produced by mitochondria or by chloroplast. The combination of stigma and intermediate processes till flagellum movement corresponds to informational processor simple on-off reflexic control.

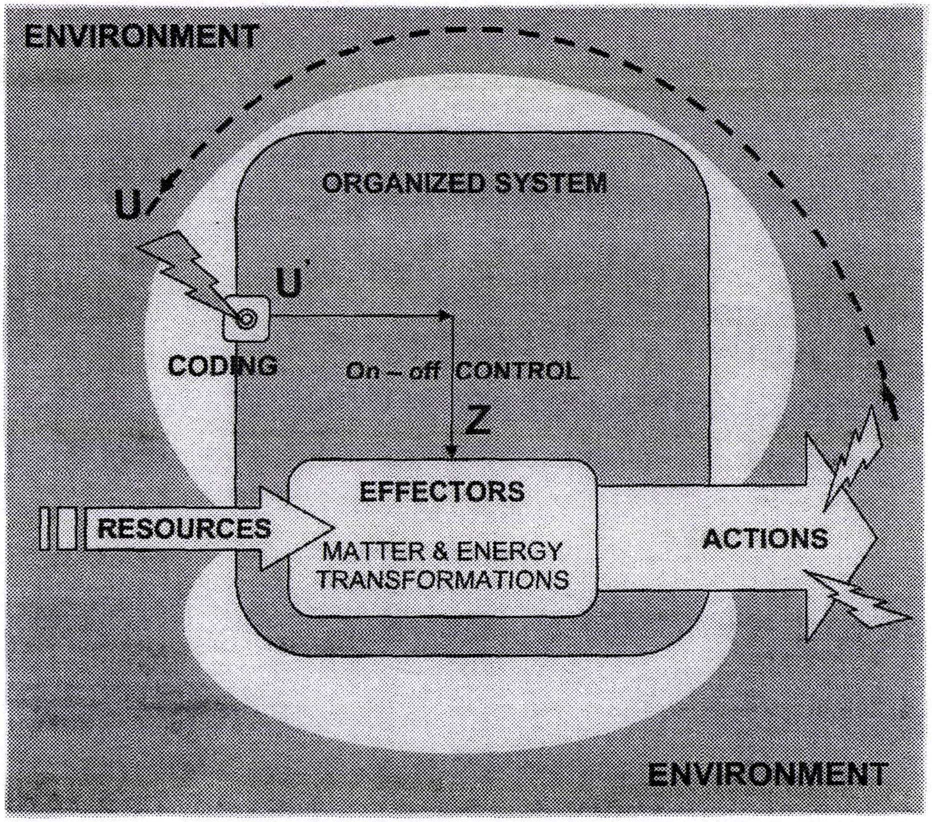

Figure 3: The simplest functional organization with informational control by reflecting neural networks

Multicellular organism of the same organizational level but with neural system is mollusk *Spisula*, in what photoreceptors' reaction to moving shadow edge controls the retraction of siphon and closing of valves.(D. Kennedy, 1972). Similar reflexic control is characteristic for jelly-fishes where reciprocally organized motoric neurons in umbrella switch on or off the same effectors and control jelly-fish locomotion.

The neurostructure of the same organization level in human is a low level system that controls eyelids movements.

4.2 Multireflexic Visual Coordination

More abundant receptoric and effectoric structures of more sophisticated organisms

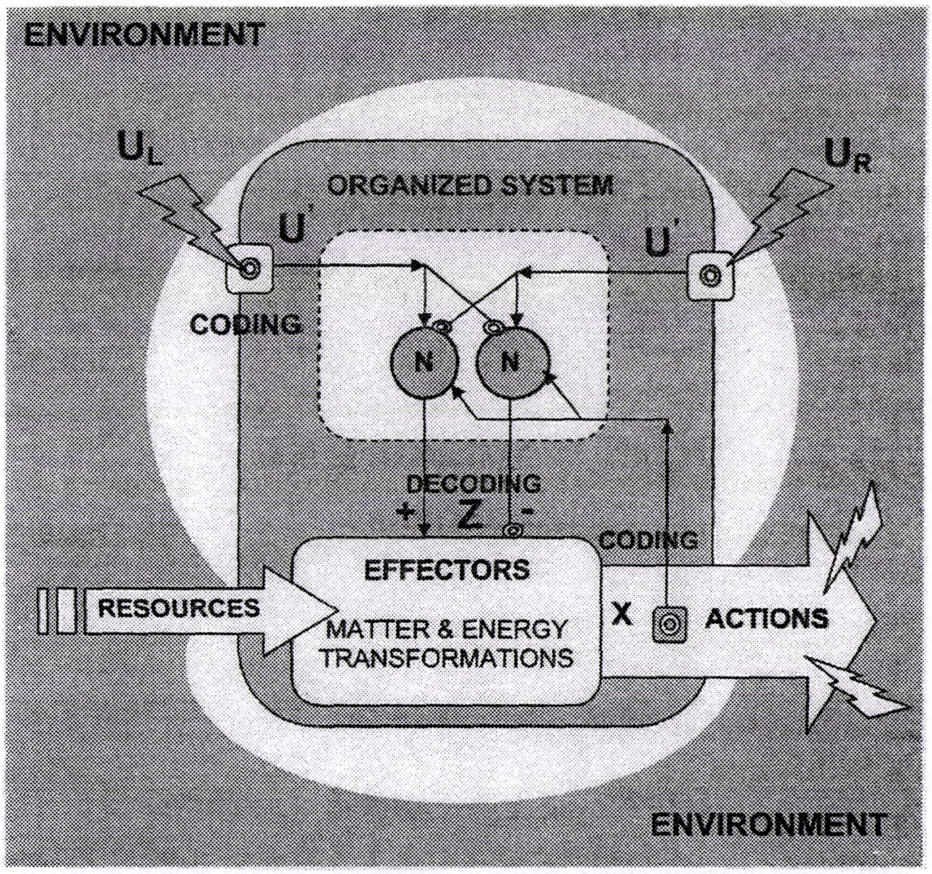

Figure 4: The simplest neural multicoordinatory organized system with combined informational control.

are coordinated by special network. Earthworm is a representative of such organisms. His photoreceptors are distributed on body surface of all segments. Earthworms avoid light, and lighting up of photoreceptors switches on the earthworm hiding reaction – reflexic movement of all body segments.

Simplified scheme is presented in Fig. 4. Environment features that are presented on left (**U_L**) and right (**U_E**) sides are encoded in photoreceptors unit and this visual information is transferred to coordinating unit that formulates commands for effectors (locomotion and positioning organs).

Such control systems can be systems with feedback or without it. Real biological systems usually have internal feedback and gather information about system state and actions of effectors.

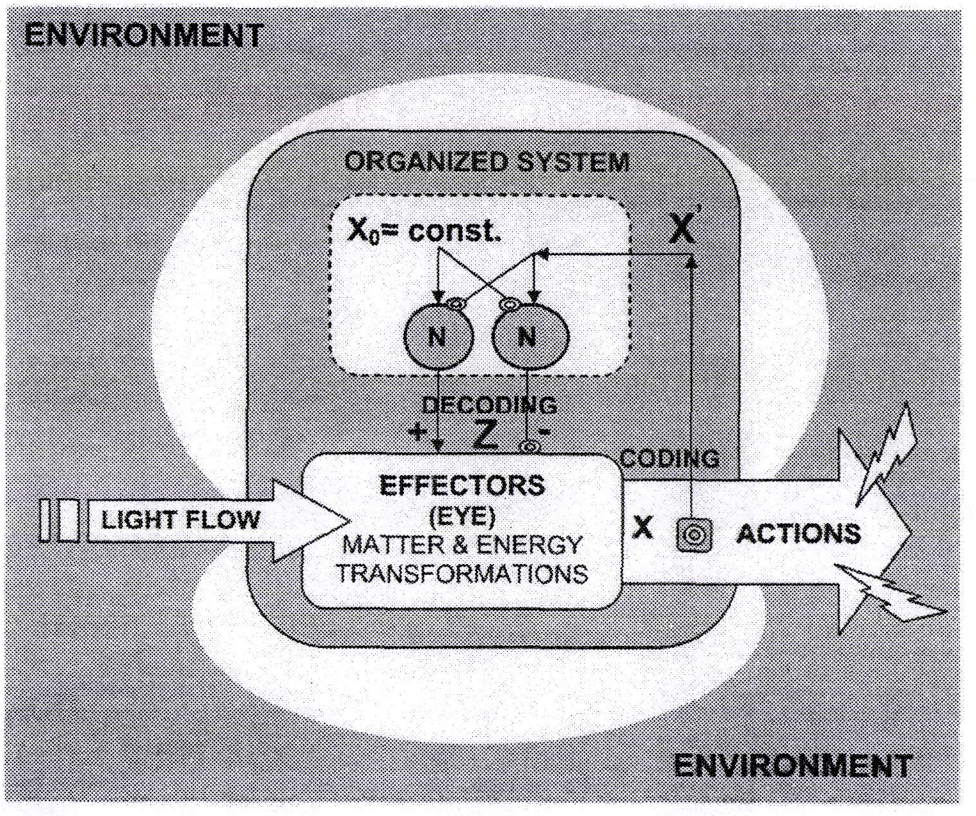

Figure 5: The scheme of simplest neural regulator, organized system with feedback informational control.

Coordinative control in human visual analyzer is implemented as non-volitional head and eyes movements that direct look to visual stimuli.

Coordinative neural structures with internal feedback were a base for emergence of regulation – more sophisticated anticipatory control.

4.3 Regulation in Visual Analyzers

Evolution of visual analyzer has formed adaptable optical part. Vertebrate eye has a lens with regulable optical power and regulable pupil (changeable aperture); both of them are anticipatively regulated by special centers. These regulative systems work with internal feedback (Fig. 5.). The point of pupil size regulation is to make luminous flux

X incident to eye retina equel given value $\mathbf{X_0}$ that is fixed in neural center and ensure the best vision. Iris muscles (effectors) dilation increases **X** when $\mathbf{X<X_0}$ and constriction decreases **X** when $\mathbf{X>X_0}$. It means that neural regulation center (controlling subsystem) is one step ahead of regulated muscles (controlled subsystem here) when it makes decision about changing of luminous flux. It can be named as *anticipative prediction.*

Similarly the optical power (curvature of surface) of lens of vertebrate eye is regulated. Here special neuronal networks that measures image contrast in central part

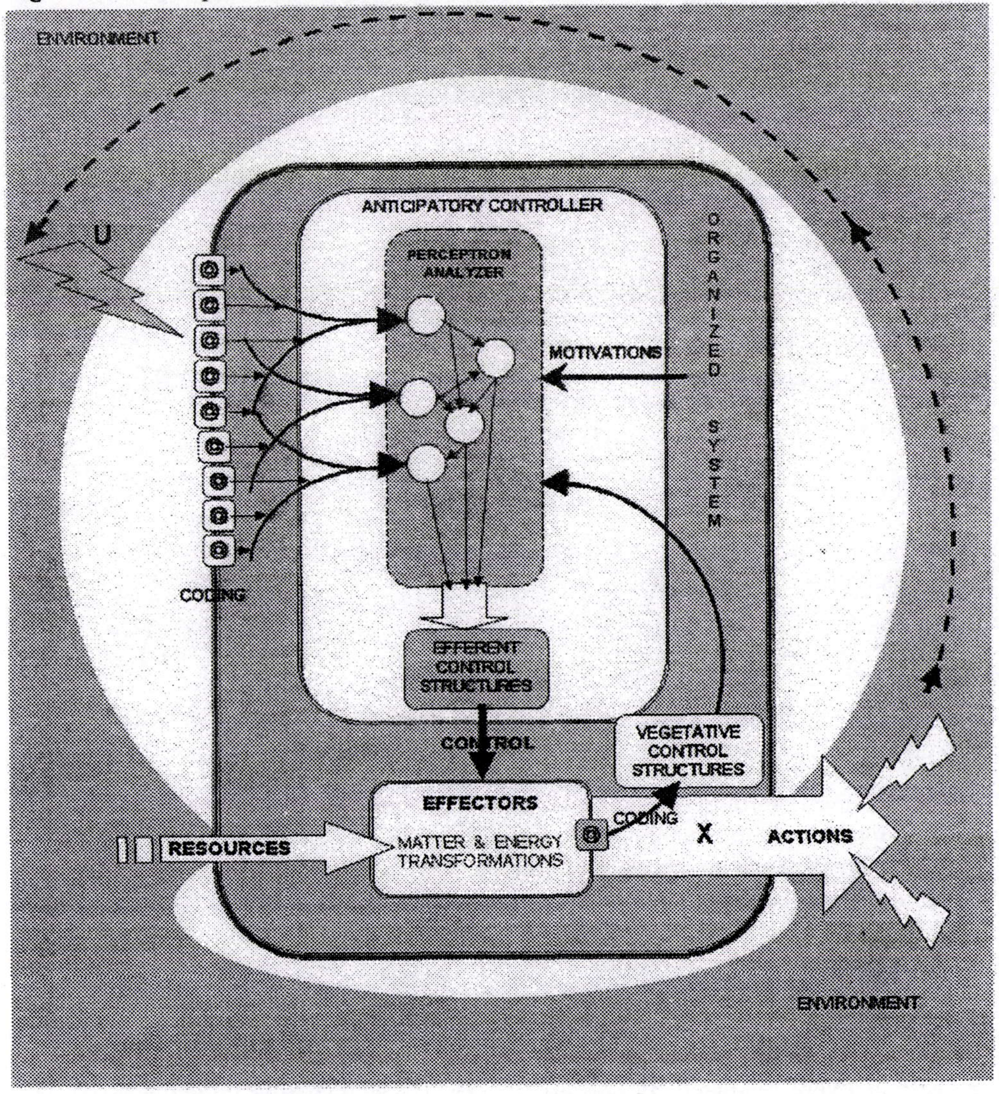

Figure 6: Simple perceptronic visual analyzer

of retina are necessary. The regulation center perpetually changes lens surface curvature and maximizes an image contrast. The neural part of this regulator searches for maximum in contrast function curve.

These regulatory neurostructures exist in reptiles but are most evolved in mammals and birds. They are parts of reciprocal non-volitional vegetative sympathetic and parasympathetic neural systems involved in vision regulation.

4.4 Simple Perceptronic Visual Analyzers

The perceptronic analyzing neuronal structures evolved in more advanced visual analyzers (Fig. 6.). Single neurons acquire "detector" properties through their receptive fields.

They are able to respond to specific properties or features of retinal image and send information to decision making subsystem that generates commands for control of effectors. Such kind of control was discovered by classic neurophysiological and ethological works of Letwin and Maturana and of other researchers. They demonstrated the detecting properties of frog retinal neurons and the correlated frog behavior in natural environment.

Similar neurons were found in birds and lower mammals. Their neurons detectors are mesencephalon colliculus superior (not in retina) that regulates the purposeful targeting of look through body and eyes movement.

Mammalian visual analyzer has the neocortex. It is another higher level neurostructure in what thinking take place..

4.5 Analysis by Synthesis in the *Area Striata* as Anticipatory Control or Visual Thinking

The functional organization of neuron layers of Brodmann area 16 in primary visual zone of mammals is especially interesting. Morphological, neurophysiological and computational research had generated most abundant experimental data and had given many theoretical models, but principles of area 16 organization and functioning are very hazy yet. Interpretations of functioning of *Area Striata* can enclear the anticipatory principles of neocortex in visual and general thinking.

More detailed model of visual analyzer based on image analysis through synthesis or closed-loop coding-decoding procedure is presented earlier (Kirvelis, 1970, 2000, 2002).

The highest step of evolution of visual analyzer neural part is the formation of visual neocortex with qualitatively new information processing capabilities. This new neurostructure functionally is higher than structures that work on simple reflexic level (eyelid movement control), multireflexic coordination level (non-volitional control of body and head movement), regulation level (control of pupil and lens), analyzer coordination level (non-volitional eye movement control), and perceptronic analyzer level (eye response to moving or color stimuli through the colliculus superior).

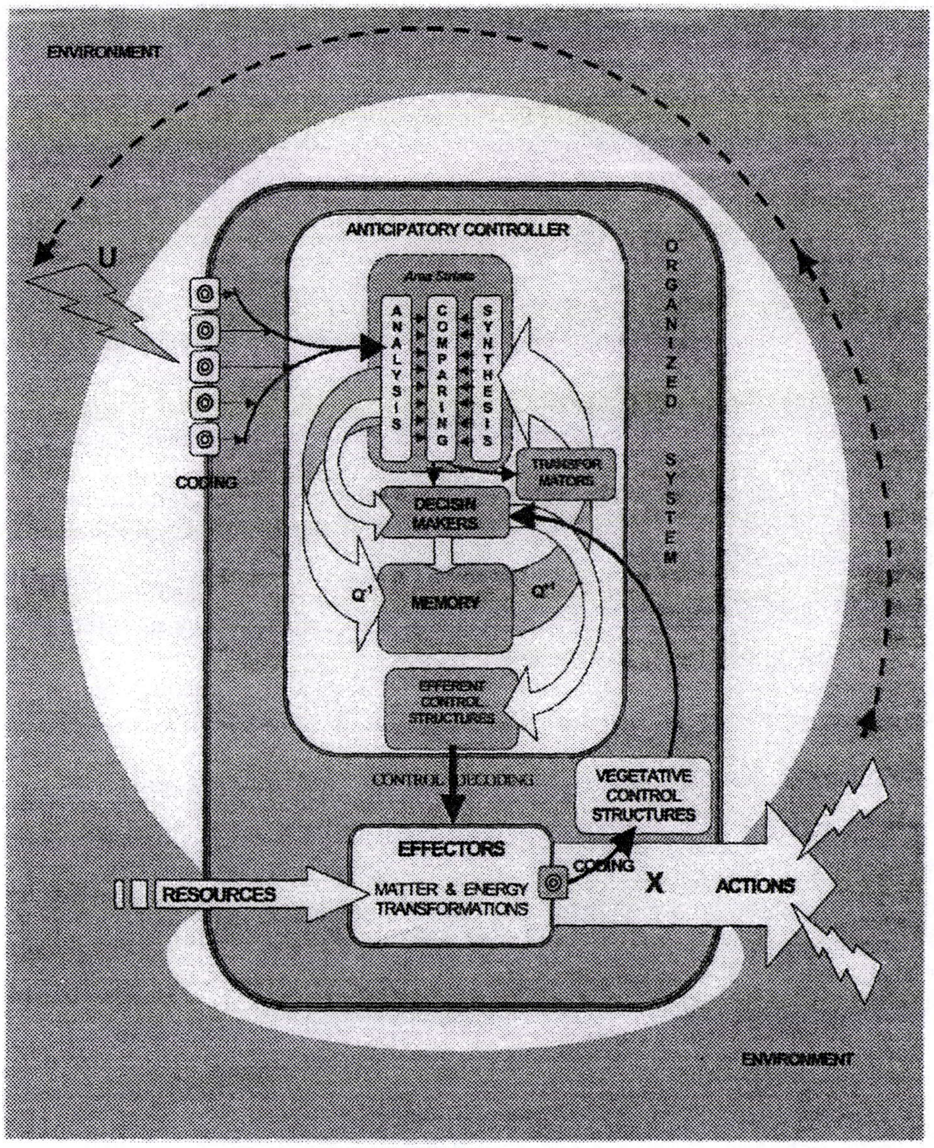

Figure 7: Visual controller with analysis by synthesis without sensory screens

It uses virtual imitative models and is a vehicle for visual mental thinking (term of cognityve psychology). This feature is illustrated here by generalized schemes (Fig. 7. and Fig. 8.) that represent mammalian visual analyzers.

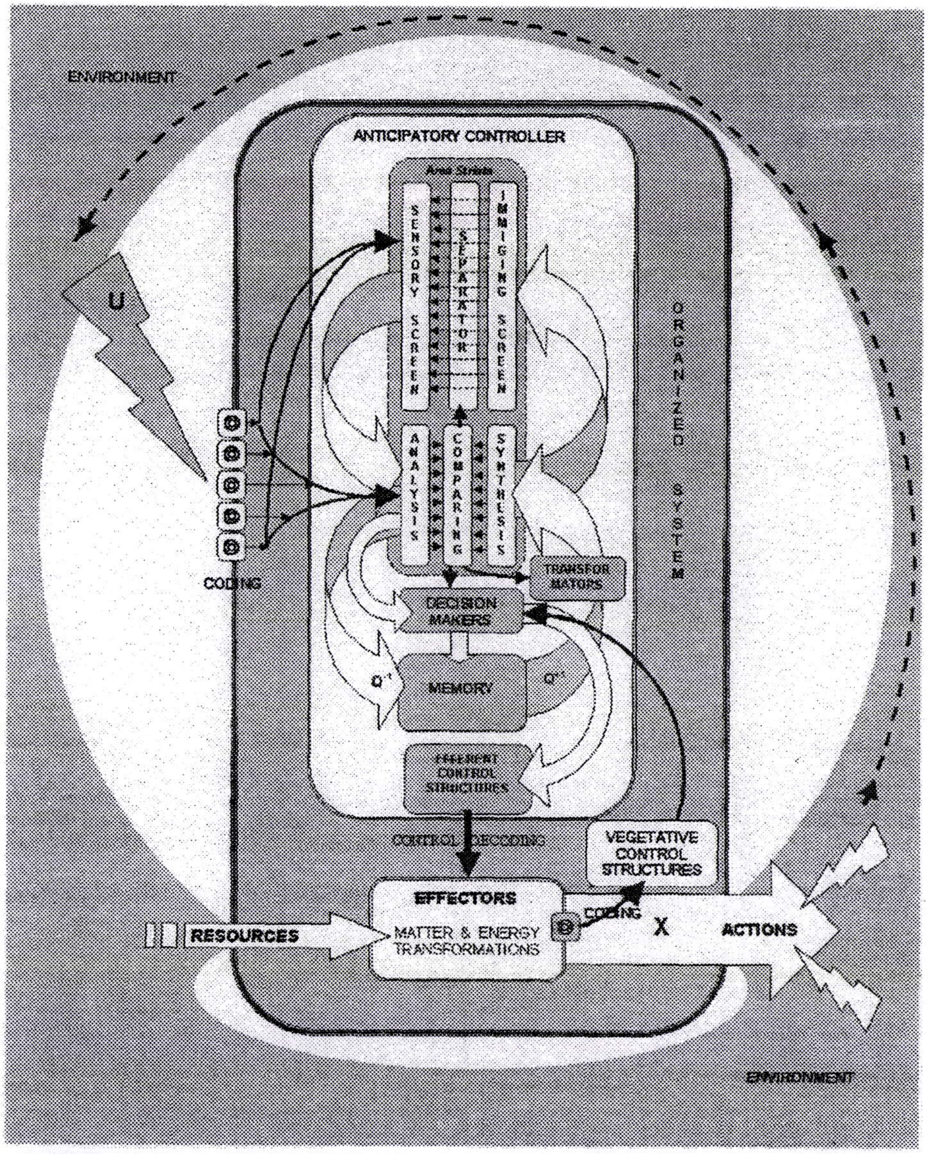

Figure 8: Visual controller analysis by synthesis with sensorics screens

Receptoric structures code the environment images and their changes and send coded information to primary visual zones of neocortex. Here properties of visual images are analyzed in detail (Fig. 7). Analysis results are used for primary perceptronic recognition, for comparison with reconstructed image from memory and for registering in memory structures. Continual analysis and comparison of retinal images to anticipated images that are recollected from memory on basis of environmental situation and motivations are specific to visual neocortex. This cyclic analysis-by-synthesis or internal distinctly anticipatory closed-loop coding-decoding procedure carries imitative cognitive modeling. The results are used in generation of pragmatic behavior models for current and future actions. All this activities are used:

1. to generate gnostic cognitive models that must correspond to reality as exactly as it is possible. The motivation helps to shorten search of most corresponding models in memory.
2. to generate pragmatic models that are used to change reality according plans generated in mind. The last feature is especially characteristic for human mind.

Maybe this imitative Analysis by Synthesis with closed-loop coding-decoding feedbacks is an essence of thinking, because thinking is mental creation of schemes (models) implemented in structures of neocortex.

IVc layer and border of III–IVa layers of striate cortex of diurnal monkeys and humans have many small neurons with intertwined (entangle axons and innervation from receptors. These neurons have concentric receptive fields. This and other similar facts give a possibility to think that these neurons in IVc layer are assembled to *sensory screen for incoming images*. The excitation of sensory screen arouses the subjective sensation of visual image (Fig. 8.). The similar neurons from III–IVa border can be *synthesis sensory screen*. Both these sensory screens normally maybe are separated by special structure - separator. In pathological cases or in night-dreaming when this separator is inactive humans and animals see hallucinatory images or visual night-dream images. Here the synthesized images are transferred to *incoming sensory screen*, and person experience them as real incoming ones. This mechanism explains night-dream image generation and other similar unexplained psychological phenomena.

Most unknown part in this analysis through synthesis system is mechanisms and principles of fixation of sensory information in memory structures. Some cases of psychopathological disorders demonstrate that memory in neocortex is phenomenally extensive. It chronologically registers all seen events and objects independently on their conscious perception.

This interpretation of analysis-by-synthesis gives a possibility to understand anticipatory activities the importance of what was emphasized by R.Rosen (1985)

5 Conclusions

1. Animals are entities with obvious anticipatory multilevel control systems.
2. Nervous system can be interpreted as controller with anticipatory control principles when animal is interpreted as organized control system consisting of two subsystems (controller and controlled) that are closely coupled by informational closed-loop coding-decoding procedures.
3. Functional evolution of nervous system is an evolution of anticipatory control systems.

4. Five levels of anticipatory control can be seen in animal visual analyzer:
   - Simple reflection;
   - Multireflexic coordination and programmed control;
   - Regulation and homeostasis;
   - Simple perceptronic analysis;
   - Analysis-by-Synthesis without or with "sensory screens".

5. Only fifth level of anticipatory control (Analysis-by-Synthesis) represents full anticipatory (or model-based) control system that can be simulated as hyperincursive computer program. Other levels of the control represent anticipatory features that generate lower or higher level predictions that can be simulated as incursive computer programs.

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