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THE SYSTEMIC APPROACH TO THE STABILITY AND PLASTICITY OF NEUROPHYSIOLOGICAL PROCESSES DURING ADAPTIVE BRAIN ACTIVITY

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The problem of the stability and adaptability of regulatory processes is considered, taking as a point of departure N. P. Bekhtereva's theory regarding stable pathological states, and inflexible and adaptable links in control systems. The need to introduce a probabilistic approach is emphasized. Generalizations are made on materials relating to the connectability of the separate components of the biorhythms of functional systems, and to the stability of their amplitude–frequency characteristics. The corpus of facts permitted the successful development in clinical practice of functional biocontrol and feedback.

Key Words: adaptability, stability, electroencephalogram, connectability of EEG components.

The problem of the plasticity and stability of physiological processes is germane to the theoretical and applied concerns of contemporary medicine and biology. Bekhtereva [4, 5] has presented some generalizations along these lines in her theory of stable pathological states. Closely tied in with this theory are conceptions of inflexible and adaptable links in regulatory systems. These conceptions have gained recognition in clinical practice, and have promoted the working out of methods of treatment of chronic diseases of the nervous system which are new in principle. In the laboratories of Bekhtereva, the application of a comprehensive method for the diagnosis and treatment of brain diseases has permitted the consideration of physiological and pathological functions as a unity and, in many cases, the discovery of the causes of the stability of pathological functions and of new ways of overcoming pathological states [5]. Bekhtereva [5], in developing her theory of the stability of pathological states, brings it into relation with adaptation, and emphasizes the special role of memory in their maintenance and regulation.

Works by Bekhtereva et al. [6], Gogolitsyn and Kropotov [19], and others, dealing with the coding of acoustic information in the neuronal systems of the deep cerebral structures of man, are new to the theory of memory and to the description of its finer organization.

On the basis of these fundamental results, with data at our disposal on the perception and reproduction of ecologically adequate (acoustical) signals at the cellular and systemic levels [13, 34], and having generalized both the data in the neurophysiological literature on the subliminal (nonconscious) perception of signals [24] and the materials of the section on the evolution of higher nervous activity, we have advanced a thesis regarding the fixation and reproduction of information in memory discretely, in microportions, reflecting the

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state of the brain (of its afferent and efferent sensory systems) at each consecutive microinterval of time [12].

If one accepts this thesis, then one must take it that the part of the mnemic mechanisms involved in fixation has, as it were, to be in a state of continual development [12]. Continual development is characteristic of a number of other functional systems (for example, the immune system, which has, by the way, an evolutionary growth identical with that of the nervous system [1]).

The continuity of the development of mnemic functions explains the enormous number of neurons in the cortex, more than 50 billion [35], which has increased through the ascending series of vertebrates, and which has correlated with the levels of development of higher nervous activity [12, 25].

Brain structures, particularly the cortical, are able to amass unbelievably large volumes of information in memory, upon the reproduction of which neither the discreteness of separate pieces of information, their sequential order, nor the organizational quality which was in part characteristic of the input information, are destroyed [20]. Microportions of information in memory are associated into larger blocks, matrices, and matrices into still larger mnemic constructions. In this lies the essence of the systemic role of memory.

However, at the present levels of understanding of the logic of natural neuronal networks and high-molecular-weight compounds, the true organization of memory is unknown. Nevertheless, a number of advanced models have been proposed [1, 4, 5].

Sensory information is always specific. Its flow is automatically fixed in fresh matrices of memory, in which are also fixed the reactive information of past experience. We have previously set forth the evolutionary bases of these conceptions [12].

Bekhtereva [5] stresses that it is necessary to assume the "meta-concept" of the memory matrix, because this approach permits the formulation of conceptions of the structural and functional order which is a necessary condition for the formation of stable states, and for their modification resulting from one or another intervention or from adaptations to the environment. The author states that the hierarchy and interaction of various reactions of the organism are assured by means of memory.

If the durability of the fixation of information in memory is taken as a postulate, then the treatment of the internal mechanisms of inflexible and adaptable connections, of the brain's reserves of plasticity, and of the separate functional systems of the organism, requires special discussion.

"I will not be at all surprised," writes F. Krik, "if it turns out that in nature there have preferentially developed 'ingenious' mechanisms, which have imparted considerable rapidity to evolution" ([23], p. 44). To this one might add that these mechanisms imparted rapidity to many reflexive processes, the mnemic mechanisms among them.

It is apposite to suggest that the huge mnemic capacity of the brain permits the storage of a multitude of reserve control programs linked to the evolutionary and individual experience of the species and the organism, as much as it does the storage of constantly functioning regulatory programs which determine the stability of functional systems. The aggregate multiplicity of the sets of these programs is apparently very great. The daily experience of man (speech, music, gestures, work habits, etc.) attests to this. The higher vertebrates are also capable of recalling great masses of information (the gestural language of the monkeys, systems of spatial orientation signals, the recall of hundreds of food caches by the nutcracker, the squirrel, etc.). We believe that the actualization of reserve control programs is nothing other than a special means of functioning of the adaptable links described by Bekhtereva. The succeeding mechanism, which imparts variability to physiological processes, is connected with the reticular formation (with the activation reactions), inasmuch as its stimulation does not change the structure of a vocal response, but exerts a strong influence on its amplitude and on the interval between repetitions, i.e., the strength of the response-reaction [13, 15]. Destruction of specific projective and associative nuclei completely changes the character of the vocal response, but it does not affect the character of the modulating reticular influences.

It must be supposed that in the higher vertebrates a considerable portion of the programs of adaptational regulation is concluded at separate levels of the brain, prior to exiting into the effector systems. But this property requires a high degree of reactivity of the regulatory links, a capacity for rapid return to initial state, i.e., the large reserve of regulatory stability that was in fact demonstrated in quantitative studies of the stability of brain regulatory systems [7, 8, 14, 21, 22], to be a measure of their adaptational capacity. For the quantitative analysis of the characteristics of adaptive self-regulation, stability criteria generally accepted for cybernetic self-regulatory systems were used [8, 10, 11]. These are criteria of regulatory, entropic, and structural stability of a functioning system in various conditions of activity (at rest, during information processing, under extreme loads, and in the adapted state).

The method of calculation of active search-free models with the aid of so-called automatic parameter control, and the approximations of the integral of the bioelectric process (the EEG) by a second-order linear differential stochastic equation, is one of the well-substantiated methods for the statistical determination of the above-indicated criteria [21, 22]. The criterion of regulatory stability of a self-regulatory system is the capacity to return to the initial stable state following the cessation of the perturbation of the system. The evaluation, which has a mathematical expression equivalent to that of informational entropy, of the entropy of the distribution of the probabilities of the coordinates of the control system provides a representation of the system's degree of organization. This criterion of entropic stability is sufficiently sensitive to the manifestation of adaptive reorganization of the current state of the brain [21] and, consequently, provides a quantitative evaluation in probabilistic fluxes of the level of adaptive self-organization, i.e., an evaluation of the whole system of the brain's adaptable connections and their correlations. Structural stability, discoverable through sensitivity functions, reflected the capacity of the system to preserve its previous state in the presence of small perturbations. Indices of the regulatory and entropic stability of the system of functional brain state regulation experience constant fluctuations, contingent upon internal rhythmic processes. Some of these rhythmic processes increase stability; others, on the contrary, decrease it. These fluctuations are observed under all conditions of brain activity, but their amplitude and the duration of stable and unstable conditions prove to be dependent upon external influences (the processing of information, stress, adaptation, etc.), and on the individual-typological differences of man. Stable states of the bioelectrical processes of the brain prevail in individuals with high adaptability over the unstable, and are in sufficiently large supply, whereas in individuals with low adaptability there is a notable prevalence of unstable states, along with low supplies of stable states [21, 22].

Calculations have also shown that in individuals with high adaptability the organization of rhythmic control processes, as well as their sensitivity and immunity to noise, are greater than in individuals with low adaptability [21, 22]. Since the regulatory and entropic stability of the human brain increases under short-duration functional loads, and since in the process a linking up with supplemental adaptable connections must inevitably occur, there are then grounds to suggest that the individual-typological features of brain regulatory systems depend to a known degree on the general structure of connections (activating, inhibitory, stabilizing) between the cortex and the deep brain formations.

We regard the adaptive control of brain activity as a whole as combinatory; this control is, according to Bekhtereva [4, 5], inflexible, programmed, on one hand and, on the other, it is adaptable, linked to tracking systems with whose assistance auxiliary control programs are engaged or inhibited.

In addition, it is necessary to emphasize, in such a treatment, that the phenomena of inflexibility or adaptability have a probabilistic character; they mutually supplement one another, dependent upon the conditions of their regulation and state, and upon the functional interaction of the regulatory processes as well. The latter especially has been studied over the course of the last several years [10, 11, 16, 17, 22, 29, 31-33]. Through the connectability and general biorhythmicity of their structure, new aspects of the functional, temporal, and probabilistic organization of the neural mechanisms controlling adaptation are being discovered [26].

At the Department of Ecological Physiology of the Institute of Experimental Medicine, Academy of Medical Sciences of the USSR, a large series of experiments, devoted to the analysis of the parameter of connectability, from the functional biocontrol of neurons to the behavior of man and animals in probabilistic environments, has been carried out [11, 27]. The early experiments with individual neurons, neuron populations, and neuromotor units [11] have shown that the effect of associative amplification (or inhibition) of discharges is de-

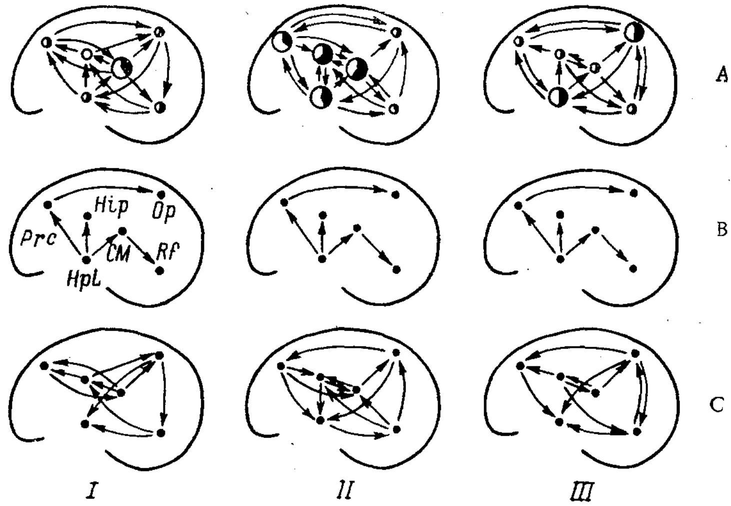

Fig. 1. Graphs of the interaction of cat brain structures before (I), during (II), and after (III) the prolonged influence of a physical factor (20 days). See further explanation in text.

termined by the synchronization of biologically positive (or negative) reinforcement with low-frequency components of the biorhythms of these discharges. It is precisely associative amplification (or inhibition) which also lies at the base of electroencephalographic changes, cardiac contraction frequency, the psychogalvanic skin response, and other vegetative functions. The data obtained support the assertion, according to Bekhtereva, that associative control through the linking up with supplemental programs which, as it were, play the role of one of the elements of an adaptable link, is the basic mechanism of active regulation by inflexible links. This result, we believe, is in agreement with the artificially stable functional link I and II (ASFL I and II) effect (according to Smirnov and Borodkin [28]).

On the theoretical level, the conditioned reflex governance of the bioelectrical activity of the brain, muscles, skin, and other tissues [9] attests to their relative independence, as it does equally to the relational role of the separate structures of the brain. Apparently this is a result of the distributive character of memory among the cortical fields and the subcortical structures [5].

In studying the interaction of structures, we [33] took note of the fact that inflexible and adaptable links (programs) of regulation by brain bioelectrical activity can have a cyclical character, with cycles of various periodicities and with nonidentical densities of connections in separate structures of the brain. At the same time, cycle dynamics which are similar in principle have been found in man and animals; the structure of these cycles depends on differences in the adaptive level of a given human being, on the state and depth of adaptation, and the period of action and extremeness of factors. Constant, inflexible cycles, independent of the above-cited factors, and, contrariwise, cycles dependent on them, are coming to light. We have designated the latter as adaptable cycles. Connections of a similar type have been discovered in experiments on cats, in which the interactions of a series of brain structures, acted upon by a physical factor, were studied (Fig. 1). In this figure, A shows all the connections before, during, and after the effect; B shows the unchanged portion of the interstructural connections (inflexible links). It is apparent that their pacemaker is in the hypothalamus, which shows the primacy of the studied states' connection with homeostatic regulation. In column C of the same figure are shown the adaptable links of the interstructural interactions, whose density is somewhat higher during the influence of the physical factor. They chiefly organize the interaction between the deep structures. It is possible that this is linked to the prolonged character of the action of the physical factor (20 days) and, in particular, with the influence of microwaves principally on the homeostatic processes.

Even more graphic findings on the probabilistic nature of connections were obtained from research into the biorhythmical structure of the electroencephalogram using combinatorial analysis. The methodology of measurements has already been presented in a series of articles [2, 16]. It has been established that it is possible, by evaluating the probabilistic structure

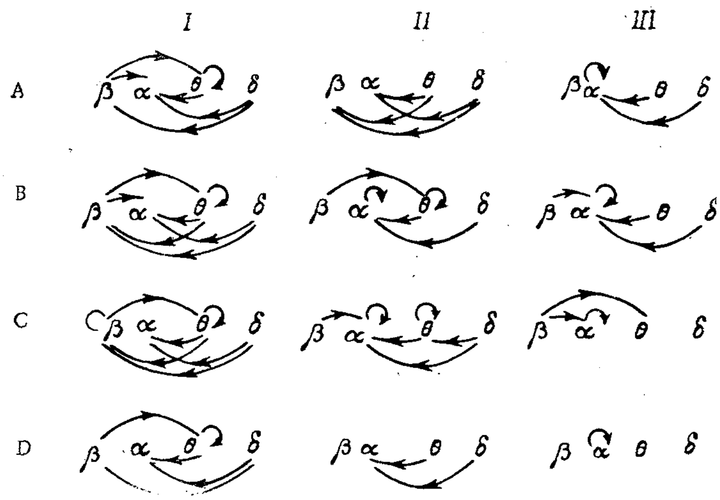

Fig. 2. The individual—typological features of the intercomponent connectability of the human EEG during periods of adaptation in Antarctica. I-III) High-, medium-, and low-adaptable groups; A-C) beginning, middle, and end of the wintering period; D) invariant set of connectabilities for the corresponding groups during a number of wintering periods.

of the connections between the components of the EEG, to distinguish three groups of individuals by the level of adaptability. Not only are these groups distinguished according to the levels of plasticity and stability of the amplitude—frequency characteristics of the EEG, but they are tied as well to the diversity of the functional relationships among the separate components of the EEG [29, 30]. If it is held that the EEG represents functionally invariant components which determine, in the given microinterval of time, the functional state of the brain's neuronal fields, then the relationship of the components to one another in time and space will be nothing other than the programs of brain state regulation. The designation of the general character of the EEG as a pattern is an accepted convention in neurophysiology. The analysis of intercomponent relationships does incorporate within itself the concept of pattern, but it in fact provides broader and more profound information about the biorhythmical structure of neurodynamic processes [3]. Thus, diverse, statistically stable connections are found in group I individuals: the generation of α-wave spindles and the α-, ϑ-, and δ-waves, guarantee with high probability (0.55-0.81) the succeeding generation of α-waves. Thus, Soroko et al. [23] successfully generalized this finding, having singled out the α-rhythm as the functional nucleus of group I individuals. Should this probability decrease somewhat, then the level of adaptability falls. Thus, in the case of group II individuals two components, α and ϑ-, fulfill the role of functional nucleus, while in group III individuals this role is played by the ϑ- and δ-components.

These regularities appear especially graphically during wintering in Antarctica. At the onset of adaptation, the initial structure of the connections among the components of the EEG loosens somewhat (the destabilization phase). However, by the end of the wintering period, the connections of the components with rhythms fulfilling the function of "nucleus" manifest themselves more clearly [29].

The biorhythmical structure of group I individuals is, as a whole, not only diverse and abundantly saturated with high-probability intercomponent connections, but in fact it continues to become more saturated with them during the course of adaptation. A similar picture is observed in group II individuals. On the contrary, among group III individuals the meager, unstable connections between the components of the EEG continue during adaptation to be unstable, not only at the beginning and middle of the wintering period, but also through the period of its conclusion [3]. Dynamics of this type are presented in Fig. 2. It is apparent that the unchanged part of the graphs, which in our opinion represents the inflexible connections, is more richly evident in group I individuals (I, D).

The data obtained show that the level of adaptability is determined by the biorhythmical structure of the EEG in microintervals of time. An abundance of high-probability connections, in particular those with dominant rhythms, between the components of the EEG in adaptive individuals, indicates the best self-regulation (internal control) of the neurodynamic processes in the system of homeostasis and memory.

Inasmuch as different functional nuclei in the biorhythmical structure of the EEG are manifested in the three designated groups of experimental subjects, there then exists the possibility of coordinating these features with the relative dominance of distinct levels of the brain with component control of intracerebral homeostasis. In group I individuals there is cortical dominance; in group II, cortico-limbic; in group III, limbico-brainstem. In this connection, the increase in neuroticism from group I through group III (Eysenck test), and in personality and reactive anxiety (the personality anxiety reaction test), the lowering of activity, mood, and capacity for work (mood and activity reduction test), the higher adaptability and stability under stress in group I and group II, and the elevated tendency to inertia and work-tension in group III (Cattell test), become understandable. Analysis of independent physiological systems by the method of construction of functional models of regulatory and biorhythmical processes [17, 22] also attests to the fact that there is a greater regulatory range and a smaller tendency to inertia in the adaptive group.

Thus, the systemic analysis of the stability and plasticity of the biorhythmical structure of neurophysiological processes demonstrates the complex combination of inflexible and adaptable connections in the process of regulation of functions in the course of adaptation, and of the stabilization of various states. The stability of this stabilization depends on the correlation of inflexible and adaptable connections, and also on their controllability by an associative pathway. It is precisely this circumstance which reveals the true nature of adaptation in its individual manifestations, and the mechanisms of so-called biocontrol in experimental and clinical practice [11].

Bekhtereva's conception [4, 5] of the stable pathological state, as well as the material set forth above, form the theoretical foundation for methods of functional biocontrol which are based on the mobilization of the brain's functional reserves, and on the possibility of the selective search for adaptable connections which, in combination with inflexible connections, give rise to new functional states of the brain.

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