Neuroscience and Behavioral Physiology, Vol. 27, No. 5, 1997

NEUROBIOLOGICAL BASIS OF CREATIVITY

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UDC 612.82/.83+155.4

There is an enormous gap between the extreme complexity of the phenomenon of human creativity and the limited extent of our knowledge of brain activity. In this situation, it would naïve to suppose that a full description of the neurophysiological mechanisms of creativity could be provided. Our aim is much more modest: to indicate those areas of contemporary neurobiology which we believe could best be compared with human creative activity.

At the end of the twentieth century, it became clear that versatility and the ability to make choices from unpredictable alternatives lie at the basis of self-development in nature. Only in an unstable system can unique events occur, producing new and higher forms of organization [21]. This universal principle is especially clear in the process of the evolution of living beings and in the creative activity of an individual brain.

I would like to emphasize that the analogy between human creativity and "the creativity of Nature" is not a simple metaphor illustrating the author's thoughts, but is evidence for one of the fundamental principles characteristic of all life, where its higher social forms are a frequent, albeit qualitatively specific, case. "During biological development," wrote Volkenstein, "not only does the value of information available to the body increase, but the ability of biological systems to select valuable information also increases... Selection of valuable information provides the basis for all creative activity in humans" ([15], p. 557).

The author of evolutionary theory himself, Darwin, described an analogy between the evolution of languages and speciation of biological organisms, in Chapter 14 of "The Origin of the Species." Timiryazev ([25], p. 226) suggested that pure talent required a combination of two properties: "an amazing productivity of imagination and a no less amazing fine and rapid critical ability... an immense productivity and relentless criticism are thus a major principle both of human creativity and of the creativity of nature."

The area of study analyzing the features of the similarity between the evolutionary process and brain activity has in recent years been termed "neurodarwinism" [31]. As in the process of evolution, the success of individual adaptation to the environment by means of learning shows a considerable level of dependence on variation in the material subject to selection. In the case of learning, the accumulation in memory of information with unclear practical value, i.e., information which is not important or of immediate relevance to the organism at the moment of its acquisition, may provide an example of the existence of preadaptation to an unpredictably changing environment [13]. "The nervous system in animals, which is able to carry out complex sensorimotor acts," proposed Edelman, "adapts successfully to complexes of incoming information which it has never previously encountered in the history of the individual or species. It is difficult to provide support for this premise, though it would appear most defensible in its application to humans" ([30], p. 74).

However, any attempt to model learning as an interaction between the processes of variation and selection will be fruitless until a criterion for selection can be introduced into the model. In particular, the assortment of material subject to selection must be limited in a controlled way to prevent the selection of variants from losing its adaptive sense. Thus, having eliminated all kinds of action programs from his model, Edelman needed to introduce a system of values, without which the model would not work [32].

As an advocate of the acquisition of new world knowledge by active seeking, Karl Popper contrasted his views with Pavlov's theory: "I propose that the organism does not wait for the passive repetition of an event (or two events) in order for memory to record the existence of a regular relationship. The organism actively tries to unify the world using hypotheses about relationships... I would replace the theory of the conditioned reflex with this theory of actively making and rejecting hypotheses (the variation component of natural selection)" ([35], pp. 137-138).

Institute of Higher Nervous Activity and Neurophysiology, Russian Academy of Sciences, Moscow. Translated from Fiziologicheskii Zhurnal imeni I. M. Sechenova, Vol. 81, No. 11, November, 1995, pp. 1-9. Original article submitted February 24, 1995.

0097-0549/97/2705-0585$18.00

Agreeing with the general position of Popper, I would like to note that he paid no attention to the first stage of acquiring any conditioned reflex: the generalization stage. Pavlov provided the first description of this phenomenon in his Nobel lecture in 1904 in Stockholm: "The point of the central nervous system which is strongly stimulated during an unconditioned reflex directs weaker stimuli to itself, these weaker stimuli coming simultaneously to other points of this system from the internal or external worlds, i.e., the unconditioned reflex temporarily opens a pathway to this point for all these stimuli. The conditions which affect the opening and closing of this pathway represent an internal mechanism... the finest adaptation of the animal body" ([18], p. 44). Thus, at the generalization stage it is possible to produce, for example, a food response to a stimulus which has never before been combined with food reinforcement. Thirty years later, writing about the results of experiments in monkeys, Pavlov compared the generalization phenomenon and the subsequent inhibitory response to nonreinforceable stimuli with the processes of scientific creativity: "The practice of scientific thought is directed firstly to obtaining more constant and precise connections, and secondly to rejecting any random connections" [18].

Generalization as a stage in the active search for vitally important objects is constantly encountered in the natural behavior of animals. A just-hatched chick pecks any object which stands out from the background and is of a size comparable with its beak. Later, the chick learns to pick only those objects which could serve as food. The smile reflex in children can initially be elicited by any approaching human, but later only by a recognized face.

The neurophysiological mechanisms of the generalization stage of the conditioned reflex are virtually the same as those of the dominant phenomenon described by Ukhtomskii, as was demonstrated by Pavlygina [19]. According to Ukhtomskii, the dominant is the temporarily prevailing reflex system with a primary focus in a particular brain region, which controls the operation of nerve centers at a given moment in time, and determines the vector of behavior. A formed dominant has four typical properties: stable excitation and elevated excitability, which produce the major property of the dominant — the ability to summate very diverse stimuli, and, finally, pronounced inertia. The characteristic features of the dominant are seen virtually every time we see the generalization stage of the conditioned reflex. Kozhedub's [10] simultaneous analysis of membrane and synaptic mechanisms operating during the acquisition of an analog of the conditioned reflex revealed a temporary elevation of cellular excitability, with long-term retention of increases in the efficiency of synaptic connections. Data on increases in cellular excitability on the day after presentation of combinations demonstrates the stability (inertia) of this membrane plasticity. These results support the conclusion that it is membrane plasticity which determines the dominant properties of the generalization stage of the conditioned reflex, with parallel changes in cellular excitability in the cortical projections of the combined stimuli.

The ability of a dominant to respond to a very wide range of external stimuli appears to involve the hippocampus, which must be intact for responses to occur to signals with low probabilities of reinforcement [23].

Responses occurring in a dominant are far from random in nature, since their limiting factor consists of species experience and previously acquired individual experience. For example, when a dominant focus is created in the rabbit by constant-current polarization, as described by Rusinov, it is easier to obtain the corresponding response to rustling of paper than to the sound of an artificial tone. Dogs trying to escape from painful stimulation do not start a program of random trials and errors, but test those actions which in the past have led to solutions to analogous tasks. If a monkey is persuaded that a stick used for extracting bait from a deep crack is too thin and short, the monkey will select a thicker and longer stick, rather than a thinner and shorter stick.

The summating properties of a dominant are clearly seen in observations of human creative activity. Creative people generally have divergent thoughts: they seek solutions to problems from all possible directions in order to consider the widest possible range of variations. They tend to form connections between elements which at first glance have nothing in common, as with Kekulé's monkeys, Newton's apple, Watt's kettle lid, and the spider's web in the case of the inventor of the suspension bridge.

Previously accumulated experience is also found to have a limiting function in the case of human creativity. The hypothesis leading to the discovery of the periodic table could not be formulated by a person lacking extensive knowledge of the chemical properties and atomic weights of the elements, though this store of knowledge does not by itself guarantee that the hypothesis will be formed. Analysis of the biographies of 70 important composers showed that productive creativity was preceded by periods of diligent work. None of these composers created any works less than ten years after mastering their subject.

Motivation is the second factor limiting and directing the search activity of the dominant. The search becomes wider as the acuteness of need increases. If an animal is subjected to deprivation in conditions in which food-related stimuli are absent, the animals spend most of the time asleep. In an information-poor environment, the movement activity of starved rats increased by a total of 10%, while in normal conditions movement activity increased by a factor of four. Thirsty rats become sensitive to signals associated with water.

The stronger the need, the less specific the object eliciting the corresponding reaction. Increases in emotional tension, on the one hand, widen the range of engrams retrieved from memory and, on the other hand, reduce the criteria for decision-taking when these engrams are compared with ongoing stimuli: the hungry person starts to perceive vague stimuli as being associated with food. The hunger state is accompanied by reductions in the sensation thresholds for both food and nonfood smells, along with an increase in the threshold for their recognition. The type of response to a neutral slide in a number of emotional (changes in heart rate and head plethysmogram) has been shown to depend on the level of anxiety of the subject. The higher that level of anxiety, the more frequently the subject responds to the neutral slide as though it were aversive.

Stimulation of the motivational structures of the lateral hypothalamus leads to the increases in cellular excitability in cortical neurons which are so characteristic of the initial (dominant) stage of acquisition of a conditioned reflex analog. Reverse connections from motivational structures play an important role in forming the image of a signal stimulus in the microsystems of its cortical projection. Edelman designated this type of reverse connection "re-entry," emphasizing the distinction from the feedback seen in cybernetic self-regulation [32]. From our point of view, this variety of neurophysiological reverse connection is similar (if not identical) to the reverse connections described by Asratyan [3] and colleagues.

The motivation for creativity is a factor determined to an enormous extent by its productivity. The prompt, by analogy a blow for the initiation of the hypothesis, is always a response of the motivational dominant to an event which is indifferent for thousands of observations by a person. Others have dealt cards for patience, like Mendeleev, and have seen monkeys linked by their tails, like Kekulé, or a falling apple, like Newton, but the concepts of the periodic table, the ring structure of benzene, and the law of universal gravitation were prompted in no others. Prompting requires preparation: this is a rule for creative activity by the brain which has been demonstrated on a multiplicity of occasions.

Intuition always "works" for the fulfillment of the need which is consistently at the top of the hierarchy of a person's motivation. The idea that "good and evil are incompatible" is true only in relation to creativity in the areas of science, art, and the creation of new ethical norms, where the absolute imperative is the domination of the spiritual needs of knowledge and altruism. According to Mandelstam ([14], p. 126), all types of human spiritual activity have a single source and a single foundation: cognitive ability. "The human lacking love for science cannot succeed as he is not in the right state to choose" ([1], p. 124). No less obligatory is the feature of talent: this is the tendency for mastery, the need to acquire the knowledge and experience required to fulfill a creative plan (competence drive).

It is very important that formation of a dominant focus can be cryptic in nature, with no externally detectable signs. This has been demonstrated many times in animal and human experiments [20]. After rhythmic sub-threshold stimulation of the skin of the hands, to produce mild contraction of the thumb muscles, movements can be obtained in response to switching on of a light or by conversing with the subject. It is significant that the subject is aware only of the light and verbal stimuli, but does not notice the thumb movement.

Members of creative professions — inventors, scientists, writers — have often noted that they are not aware of the most demanding stages of their work; this is not controlled by consciousness or will. "I could talk for a long time about the craft of my work," recognized Federico Fellini [26], "but usually no-one is interested. They prefer me to talk about 'inspiration' or 'importance,' about the 'meaning' of images, as though I myself had some understanding of these." The lack of consciousness of particular stages of creativity has frequently been regarded as unconscious activity in the sense defined by Freud. However, by no means all investigators are in agreement with this approach. Mandelstam wrote: "Inner hearing and inner vision, if they exist, are not the product of the subconscious... By explaining these phenomena as subconscious, we replace the higher human spheres with infinitely more primitive levels... no artificial and no cognitive activity is the result of sublimation" ([14], p. 146). Fromm proposed a similar idea [27]. Considering the language of symbols with which internal feelings, sensations, and thoughts acquire the form of distinctly tangible images of the external world (in dreams, fairy tales, and myths), Fromm considers that these images are not only basic, primitive and taboo, but also better, noble, and orientated to the future of the human race.

The mechanism whose existence is proposed in the works of Mandelstam and Fromm was termed the superconscious by Stanislavskii, to make a deliberate contrast with the unconscious and subconscious psychoanalytical schools [22, 24]. The superconscious is unconscious recombining of previous experience, which is prompted and directed by the dominant need to search for means to fulfill that need. The unconsciousness of these initial stages in clear creativity allows the resulting hypotheses and ideas to be protected from the conservatism of consciousness, from the excessive pressure of evidence coming from direct observation, and from the dogmatism of tightly assimilated norms. Consciousness retains the function of formulating problems and presenting them to the conscious mind, as well as that of secondary selection of hypotheses produced by the superconscious, first by means of logical evaluation and then in the furnace of experimental, productive, and public practice.

The activity of the superconscious is by no means the purely random recombination of traces stored in memory. Working in terms of the principle of the dominant, the superconscious forms three channels — the dominant need, previous experience, which includes the experience of earlier generations, and that defining the problem of the situation. "Fruitless combinations," wrote the mathematician Poincaré, "do not even occur to the inventor. The only ones he sees are the actually useful combinations and a few others, which shows signs of being useful, which he then rejects" ([1], p. 138).

The presence in the central nervous system of dominant foci of increased excitability not only widens the repertoire of powers to produce associations, but also leads to their rapid fixation after a single coincidence of stimulus and release from the dominant state [34]. This rapid closure of the circuit of a temporal link with an event, after which comes release from or at least weakening of the dominant state, is very reminiscent of the phenomenon of creative inspiration. Reason discovers what the soul already knows, as the writer Leonid Leonov aphoristically formulated the essence of insight. Of 232 scientists questioned by psychologists, 182 reported that solutions to scientific problems came suddenly, and not as a result of a strictly logical chain of arguments. The instantaneous inspiration with an idea of a future discovery or work of literature was described by the mathematicians Gauss and Poincaré in their autobiographies, as well as by the physicist Einstein, and the writers Charles Dickens and Robert Stevenson. The concept of nuclear decay occurred to Fermi while resting after a meal; Mozart told his mother that new melodies generally came to him while eating in a carriage.

If the mechanism of the dominant increases the preparedness of a subject by recombining traces stored in memory and widening the assortment of external signals which are perceived, making an initially unconscious selection on the basis of the dominant motivation, then the phenomenology of the secondary conscious selection is naturally associated with asymmetry in the functional specialization of the two hemispheres of the brain — the single neurophysiological factor allowing us to approach an understanding of creative thought as a dialog.

"One has to have two personalities in order to invent," wrote Paul Valeri, "one forming combinations and the other selecting the combination fitting the requirement and deciding which is the important combination of those suggested by the first personality. The thing called 'genius' is less a property of the personality making the combinations as much as the ability of the second personality to select and use only the useful combination" ([1], p. 32). The biologist Medawar ([15], p. 109) has made a similar comment: "At any level, scientific understanding begins with an imaginary, prejudiced idea about what the truth might be... at any level, scientific judgment is an interaction of two aspects of thought, a dialog of two voices - the fantasizing and the critical — a dialog, if you like, of the possible and the actual." Someone dictates and I write, as Schnittke described the process of musical composition.

According to Dostoevskii, the creativity of the poet starts with a strong impression. The soul of the poet "...is the same mine as that yielding diamonds, and without which it will not be found. Then follows the second task of the poet, already less deep and secretive, only that of the artist: having found the diamond, the artist fashions it and mounts it" ([7], p. 39). According to Mandelstam, these two aspects of the creative process — the spontaneity of the gift and the labor of converting an idea into a finished work — was abstracted by Pushkin in his images of Mozart and Salieri ([14], p. 127).

Literature, which requires the functional specializations of both hemispheres in the human, is so extensive that we can consider only those points which are directly relevant to our theme. The right and left hemispheres are "placed" differently in time coordinates. Activity of the right hemisphere is predominantly associated with supporting events occurring in the past. The left hemisphere is orientated to the future and is involved in activity each time an analysis of a new situation is needed in the search for a solution optimal for a given situation. The functions of the frontal lobes are of particular interest for understanding the neurophysiological basis of creativity. Lesions affecting frontal lobe activity are accompanied by loss of speech and muscle activity, reductions in initiative, and increased levels of distraction by unimportant events. One of the most important functions of the anterior parts of the neocortex is their role in predicting the outcome of ongoing events. The left hemisphere identifies highly likely events and formulates rules for the appearance of signals, while the right hemisphere assesses the determinacy of the situation and predicts the outcomes of low-probability events.

The clearest feature of the left hemisphere in right-handed individuals is its association with speech. Neuropsychological observations of patients with organic lesions of different parts of the brain indicate that the image of an object and its generalized symbol are formed in the right hemisphere, while its sound generalization is formed in the temporal region of the left hemisphere. Innate and acquired visual generalization occurs in the right hemisphere, while verbal mechanisms predominate in the left hemisphere. Visual perception provides a basis for thoughts about objects.

Positron emission tomography studies have demonstrated that verbal stimuli activate metabolism in the left hemisphere, and semantic analysis occurs mainly in the left frontal zone. Music activates the right hemisphere, while tasks requiring attention activate the deep temporal formations. Spectral correlation analysis of EEG traces shows that primary processing of emotionally colored visual impressions is associated with the right temporal cortex, which sends impulses via the amygdala to the frontal lobe.

The decisive role of brain speech structures in the phenomenon of consciousness had been demonstrated by neurophysiological studies. Detailed analysis of the recovery of consciousness after long comas in patients with severe trauma to the skull and brain has shown that the return of the ability to understand speech coincides with the restoration of connections between the speech motor zones of the left hemisphere and other regions of the cortex. Recording of spatial synchronization of brain electrical activity demonstrated the leading importance of the frontal-anterior parts of the left hemisphere, which select only motivationally important information, in the process of consciousness. Fully conscious processes are accompanied by foci of maximal activity in the left frontal region and the anterior speech area of Broca.

Models of the conscious solution of mental tasks by preliminary selection of possible variants were used in Ivanitskii's laboratory for studies of the interactions between the two hemispheres. Il'yuchenok [9] asked healthy right-handed subjects to solve an anagram — a word in which the letters were rearranged. The involvement of the left and right hemispheres in this process was assessed by mapping intracortical interactions, using recordings of the points at which frequency peaks coincided in different EEG leads, and indicating synchronization of the bioelectrical activity of different cortical zones, i.e., the existence of connections between them [8]. When a task was solved successfully, foci of interaction in the alpha frequency range were found in the frontal and left central temporal regions of the cortex. When attempts failed, integration centers were located in the right temporal, left parietal, and occipital regions.

An analogous method of mapping brain electrical activity was used by Kostyunina [12] during recognition of emotional states on photographs of human faces. When the emotional state was recognized, integration centers in the alpha frequency range were seen predominantly in the parieto-temporo-occipital regions of the cortex of the left hemisphere. When the emotional state was not recognized, integration centers were located in the frontal regions of the hemispheres and in the right parietal cortex.

The electrophysiological data of Kostyunina provide further support for neuropsychological observations of the important role of the right hemisphere in recognizing emotional expressions [28]; on the other hand, they agree with Glezer's conclusion [6] that the mechanism of invariant recognition of images is located in the left hemisphere of the brain.

One of the best models for the experimental study of creativity as a search for something unknown and difficult to predict was proposed by Monakhov. Subjects were shown cards with double images, one being easily recognizable, the second being masked. The subject had to press a button after identifying each of these images. Interaction coefficients for electrical processes in different regions of the cortex were mapped. Before presentation of cards, the zones with the highest levels of connectivity were in the left frontal pole and in the right central region. At the moment of recognition of the first image, 2 sec after presentation of the card, there was a sharp increase in connections in the frontal regions. Some 7-8 sec before pressing the button corresponding to recognition of the second, hidden, image, there was a sharp increase in the connections in the right frontal region. This peak then disappeared, and 1-2 sec before pressing of the button, the topographical map returned to a state similar to the baseline state [17]. High levels of activity in the frontal, occipital, and parietal regions of the right hemisphere were seen in subjects with more productive responses when solving problems requiring mature imagination [4]. Altman reported [2] that the generation of rhythmic auditory images in poets was associated with activity in the right auditory parietal cortex. The appearance of words and rhythms demonstrated an involvement of the left hemisphere.

CONCLUSION

Again emphasizing the extremely limited data on the neurophysiological mechanisms of creativity, I would like to suggest a scheme, albeit a very crude scheme, for the involvement of various brain structures in realizing a creative act as an original program for further experimental studies.

It can be suggested that the nuclei of the amygdaloid complex have an important role in defining the dominant motivation which induces the search for missing information for solving a task presented to a subject [23]. Involvement of the second formation of the limbic system, the hippocampus, widens the set of traces extracted from memory (primarily from the lower parietal cortex), which provide material for forming hypotheses [33]. These hypotheses themselves appear to be generated in the frontal regions of the right hemisphere, where they are simultaneously subjected to initial unconscious assessment, with rejection of those variants obviously not relevant to the task in hand. It should also be noted that neurons of the hippocampus, which function as novelty detectors, can respond not only to a new stimulus, but also to a new combination of traces stored in memory [11].

Coordinated activity of the amygdala, hippocampus, and prefrontal cortex gives rise to the phenomenon of insight [16], which involves the caudate nucleus, which contains neurons reflecting the pre-decision state and the moment of decision when selection is deferred [29].

Interactions between the anterior regions of the left and right hemispheres provide a physiological substrate, whose function produces the "dialog of two voices — the fantasizing and the critical" noted by creative people, and involved in the conscious logical selection of hypotheses for subsequent practical testing. The functional asymmetry of the two hemispheres of the brain now provides a much more satisfactory neurobiological basis for the interaction of the conscious and unconscious components of the creative process.

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