Neurophysiology, Vol. 48, No. 4, 2016

Indices of Coherence of EEG Rhythms in the Course of Cognitive Activity as Markers of Creative Thinking: Gender Specificity

I. Ya. Kotsan,[1] N. O. Kozachuk,[1] I. P. Kuznetsov,[1] and A. I. Poruchynskii[1]

Received July 22, 2015

According to the results of psychological testing, persons aged 18 to 21 years were divided into four groups, women and men with low and high productivity of divergent (creative, nonroutine) thinking (n = = 18 to 23). Results of EEG recording (19 leads) were used for calculation of the coherence coefficients for oscillations of the delta, theta, alpha1, alpha2, alpha3, beta, and gamma frequencies in lead pairs and estimation of integral indices of coherence within the anterior and posterior cortical regions and between these zones (interaction coefficients, IC1-IC3, respectively). EEG was recorded in the resting state and in the course of resolving convergent- and divergent-type cognitive test tasks. It was found that, during the performance of tests of both types, men with a higher productivity of divergent thinking demonstrated significantly higher values of IC1 (that characterizes the coherence in associative linkages within the anterior cortex) for oscillations of all EEG frequency ranges compared with the respective estimates for "low-creative" men. Similar increments were typical of the IC2 values for low- and mid-frequency EEG rhythms (delta, theta, and alpha). At the same time, values of the "interregional" IC3 for theta, beta, and gamma activity in "high-creativity" men were significantly lower. In women of both groups (low and high creativity), such specificity of the IC1-IC3 patterns was practically not observed, i.e., the respective aspect demonstrated clear gender specificity. The sex of the subjects and type of the performed cognitive tests could not be considered factors significantly affecting the calculated absolute IC values. The observed specificities of integral coherence indices are probably associated with different strategies of the performance of cognitive tasks in men and women. Our findings allow us to believe that the above interrelations between integrated coherence indices can be used as EEG markers of high productivity of divergent thinking in men. The more flexible strategies of thinking in women are probably related to more variable neurophysiological cortical mechanisms (compared with those in men), and this type of organization is not clearly reflected in the pattern of intracortical interactions estimated by coherence indices.

INTRODUCTION

Persons with specific intellectual processes that can significantly move away from standard "conventional" patterns are characterized as personalities with a high creativity of thinking. Such personalities are able to see objects and problems from different points of view, including nonroutine ones. When the creative personalities are faced with a particular challenge, they often propose a great number of nonstandard solutions of the respective problems, and this feature differentiates such subjects from those with a lower level of creativity. In a few words, "creative thinking" means divergent thinking, i.e., thinking within a wider mental space, out of the routine borders of stereotyped thinking [1]. The problem of identification of creative persons is at present very urgent because social and cultural needs for such individuals at the today stage of human civilization are extremely high.

At present, identification of a personality as high- or low-creativity is almost entirely based on the use of psychological (i.e., purely subjective) techniques of testing. It has been recognized that, in many cases, it is impossible to conclude convincingly on the lack of creativity or a low level of the latter typical of the given person. Manifestations of creativity are, to a considerable extent, spontaneous; in most cases such manifestations cannot be initiated or regulated voluntarily. Besides this, psychological techniques of diagnostics of creative abilities within a sampling of the persons help the examiner to identify such

[1] Lesya Ukrainka Eastern European National University, Lutsk, Ukraine
Correspondence should be addressed to
I. Ya. Kotsan (e-mail: rectorat@univer.lutsk.ua) or to
A. I. Poruchinskii (e-mail: an-poruch@ukr.net)

personalities only immediately in the course of testing, i.e., *a posteriori* [2]. Such testing does not resolve the problem of prediction of the presence or absence of creativity in the personality using certain objective markers of the respective features.

It cannot be ruled out that analysis of the characteristics of brain electrical activity (e.g., of EEG phenomena) can be fruitful for the solution of the above problem. One of the promising aspects in this field is evaluation of some typical patterns of interactions between various parts of the cerebral cortex. Many researthers consider that indices of coherence of oscillations of certain EEG frequency ranges, which are indicative of the degree of synchronicity and an in-phase pattern of oscillations in various spatially separated cortical areas, form a class of rather sensitive and, simultaneously, rather specific parameters for estimation of ongoing cognitive activity. A few authors believe that precisely these indices open possibilities to obtain definite estimates characterizing the intensity and directions of information exchange between different cortical neuronal structures. There are reasons to believe that some estimates of the coherence are in specific relations with cognitive activities of different types [3–5].

Considering the above-mentioned information and comments, we carried out a study of the patterns of coherence of EEG oscillations in representative groups of tested subjects. These persons were subjected to preliminary psychological testing and evaluation of their ability to resolve test questions requiring predominant involvement of the convergent ("routine") or divergent ("creative") mode of thinking. Experimental groups included men and women, which allowed us to estimate possible gender specificity of the above peculiarities of thinking. After this, EEG recording was performed. According to the results of such examination, coherent relations between cortical zones responsible for different aspects of associative activity were evaluated. In such a way, we tried to find objective markers of low or high creativity of tested subjects in the course of performance of the test tasks requiring the involvement of different resources of creativity.

METHODS

All subjects of the total group (98 men and 96 women aged 18–21 years), healthy (according to the results of somatic and psycho-neurological examinations), all right-handed, were subjected to preliminary psychological testing. The test results characterized the predisposition of the subject to convergent or divergent types of thinking. As to the former aspect, a test proposed by Kozlova was applied [6]; it was based on the necessity to give unambiguous answers to a series of simple questions under conditions of rapid presentation of the latter. Testing of the predisposition to divergent thinking was aimed at identifying a multi-faceted view on a definite problem and the subject's readiness to find the largest possible number of approaches to its solution. An example of such test questions is the following: "In some region, there is a large number (millions) of trees; to collect a useful product from these trees, the workers should climb to a great height to perform certain operations. Try to propose as many organizational and technical options as possible to resolve this problem" [7]. Instructions were presented to tested subjects on a computer monitor. Resolving of the test tasks of both types was performed "inwardly," and the results were recorded by the examiner after recording of EEG (see below). There was no special predisposition on creating an original product. In testing of the second type, proposition of the largest number of resolutions of divergent tasks was a measure of the efficacy.

According to the results of the described tests, four groups of subjects with the clearest tendencies for thinking of a certain type were formed; these were women with a low and a high productivity of divergent thinking (23 and 19 persons, respectively) and also men with the respective thinking features (18 and 33 persons). EEG examination was performed using conventional techniques; EEG oscillations were recorded unipolarly from 19 loci according to the international 10–20 system (Fp1, Fp2, F3, F4, F7, F8, Fz, C3, C4, Cz, T3, T4, T5, T6, P3, P4, Pz, O1, and O2). A computerized EEG complex "Neirokom" (Ukraine) was used. For each pair of leads, the coherence coefficients, CCs, were calculated using fast Fourier transform. The following EEG rhythms and subrhythms were differentiated: delta (0.5–4.0 Hz), theta, alpha1, alpha2, alfa3, beta and gamma (35–40 Hz). Frequency limits for the theta rhythm, three subranges of the alpha rhythm, and beta rhythm were set according to the individual modal value of the alpha rhythm typical of each subject. The latter parameter was estimated as the mean for a "center of gravity" of oscillations of this range in all leads in the resting state with the eyes closed. In accordance with the obtained values, frequency borders of the alpha subranges were calculated, and these data were used for the setting of frequency borders for the theta and beta rhythms in each of the above-mentioned four groups of tested subjects [8].

Usually, when the coherence of EEG of different rhythms is estimated, the number of lead pairs with high values of CCs of the respective oscillations is reported. It is obvious that such approach is not sufficiently generalized. To avoid the respective shortcomings, we calculated integral indicators of the coherence of different EEG rhythms for three types of connections, intrazonal ones for the anterior cortical regions, intrazonal ones for the posterior regions, and interzonal connections responsible for interaction between the anterior and posterior cortical regions. The respective interaction coefficients (ICs) for the above zones were calculated

The above-mentioned parts of the cortex were considered the anterior associative zone and the posterior associative zone (AAZ and PAZ, respectively) in the broad sense of these terms. Both cortical areas included associative zones *per se* (in the narrow sense of the term), primary and secondary sensory zones (visual, auditory, and somatosensory ones), and motor zones within which some associative functions are also realized.

To calculate the integral IC within the AAZ (IC_{AAZ}), the CC values for all possible pairs of leads Fp1, Fp2, F1–F8, and Fz (21 values) were taken into account. In a similar mode, 66 CC values for all "posterior" pairs of leads C1–C4, Cz, T1–T6, P1–P4, Pz, O1, and O2 were used for calculation of the IC_{PAZ}. For estimations of the $IC_{AAZ/PAZ}$, 85 CC values for all pairs of leads employed in our work were used. The following formulas were used for calculations of the IC_{AAZ}, IC_{PAZ}, and $IC_{AAZ/PAZ}$ values:

$IC1 = \Sigma CC_{AAZ} / \Sigma CC_{AAZ–PAZ}$;

$IC2 = \Sigma CC_{AAZ} / \Sigma CC_{PAZ}$, and

$IC3 = \Sigma CC_{AAZ–PAZ} / \Sigma CC_{PAZ}$.

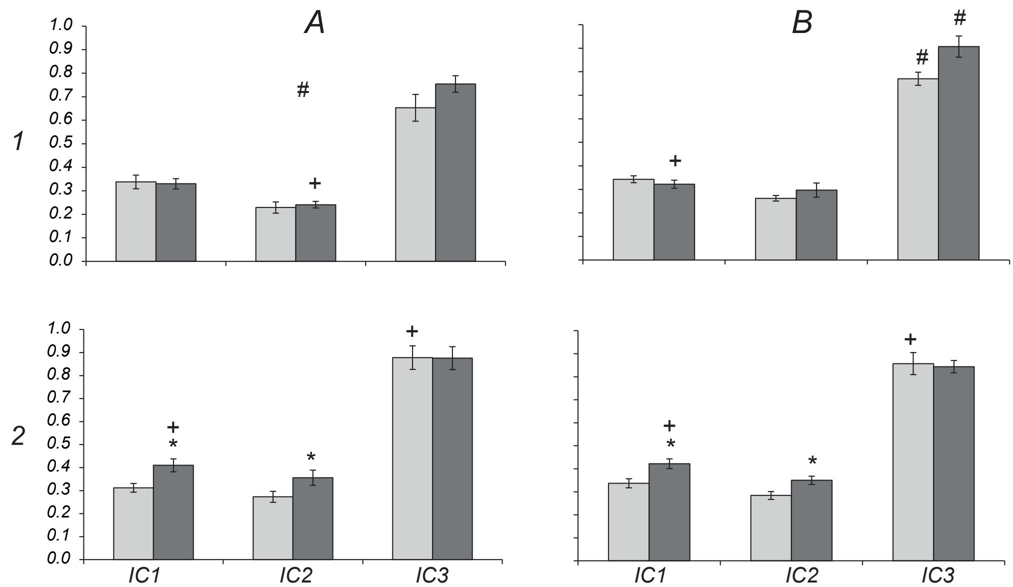
Such calculations were performed separately for the groups of men and women with low and high estimates of the creativity of thinking evaluated within the preliminary stage of the study in the course of psychological testing.

Recording of EEG was carried out in the resting state with the eyes closed and open (60 sec in each visual state) and in the course of performance of test tasks of the convergent (150 sec) and divergent (120 sec) types. During such performance, the eyes were open. After EEG recording in all four groups, we carried out correlation analysis of the IC values and indices of productivity in the performance of the convergent and divergent tasks for each experimental situation. The means and s.e.m. values were calculated for these figures, and *P* values for intergroup differences and probabilities of correlations between the above values were estimated.

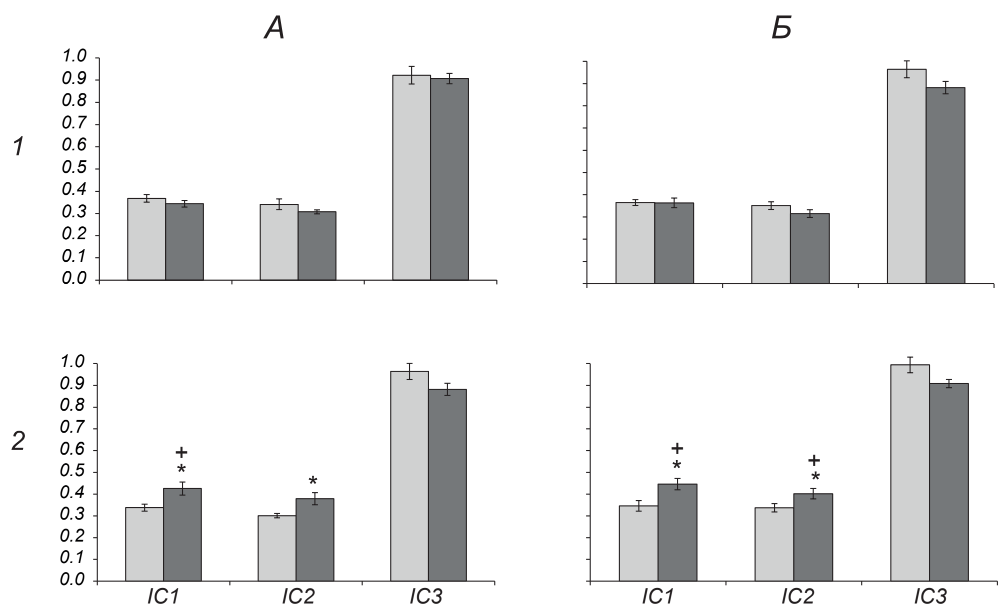
RESULTS AND DISCUSSION

It is obvious that the brain is an extremely complex system with a great number of dynamic functional connections. At the same time, certain parts of the brain specialized on certain types of operations can, in general, be differentiated. Considering this, it is believed that the posterior neocortical regions are the structures responsible for the primary analysis of sensory information and certain associative functions (both primary and somewhat more complex). The front part of the cortex (mostly frontal zones) provides realization of more generalized operations largely associated with executive functions. As was noted above, the anterior and posterior parts of the neocortex can be qualified as the AAZ and PAZ, respectively (in the broad sense of the term "associative zones").

Considering these peculiarities, the interaction of neuronal networks within the PAZ and AAZ, as well as the specificity of the information exchange between these parts of the cortex, characterized both different stages and different strategies in integral processing of information by the brain. It is logical to assume that the associative links between neuronal networks within the PAZ should characterize complex and thorough processing of primary sensory information coming from these regions [9, 10]. Strengthening of the linkages between the AAZ neuronal networks at simultaneous certain weakening of connections within the PAZ should characterize the more intense involvement of mental (cognitive) functions in general cerebral activity; These functions are, first of all, related to the work of operative memory and planning of actions [5, 11]. Such situation, respectively, corresponds to certain reorientation of cerebral activity from processing of the external stimuli to internal subjective mental processes. In turn, strengthening of connections between the PAZ and AAZ should characterize a



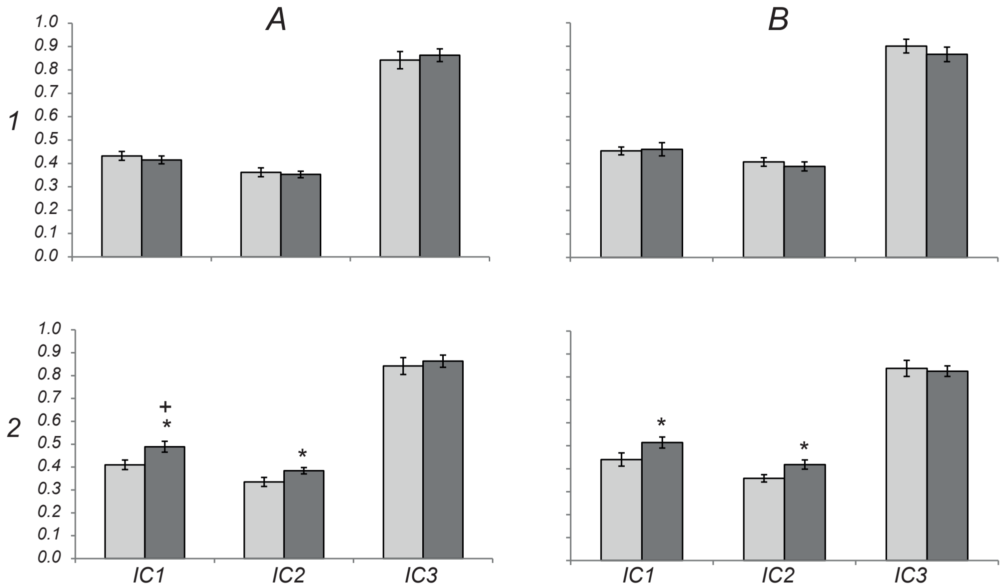
F i g. 1. Mean values of coefficients of intracortical interaction IC1–IC3 calculated for EEG oscillations of the delta rhythm in the course of performance of test tasks of the convergent (A) and divergent (B) types by tested subjects (1 and 2, by women and men, respectively) with low and high levels of divergence of thinking (light and dark columns, respectively). Means ± s.e.m. values are shown; asterisks indicate cases of significant differences ($P < 0.05$) between IC values in pesons with low and high creativity, plus signs show cases of significant differences between the respective IC values in men and women, and # signs show cases of such differences between the respective IC values at the performance of the convergent and divergent test tasks.



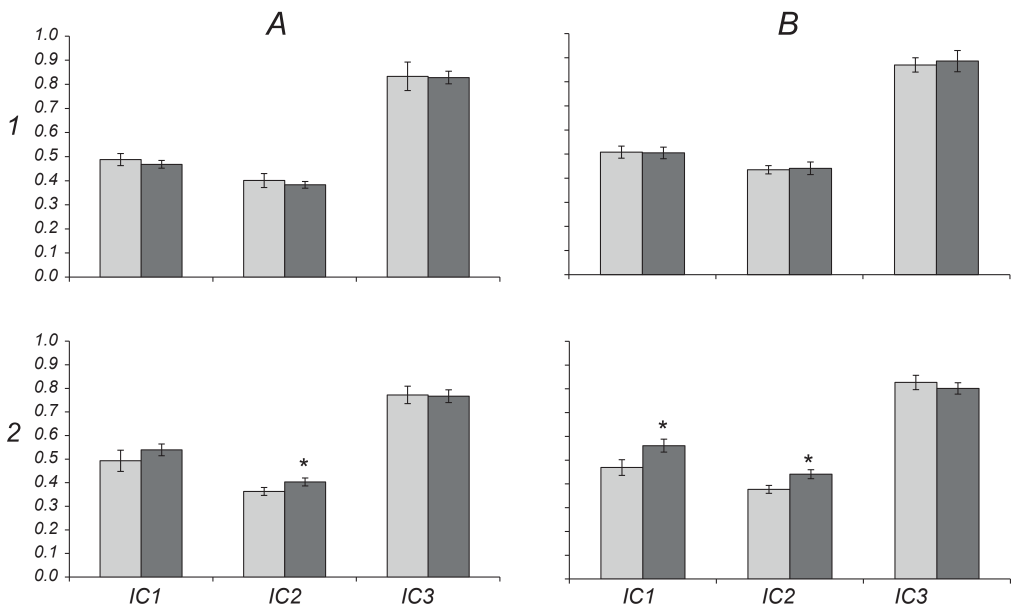
F i g. 2. Coefficients of intracortical interaction IC1–IC3 for oscillations of the theta rhythm in groups of the tested subjects. Indications are the same as in Fig. 1.

certain intermediate stage of processing of sensory information. Within the framework of such a stage, a more detailed analysis of the characteristics of external information and detection of important aspects of the latter are needed, which provide the subsequent transfer of this information to the working memory and its “embedding” in a system of the internal ideas [12, 13].

The results of our EEG study have shown that the IC1–IC3 values calculated for the resting-state period, with the eyes both closed and open, demonstrated no significant correlations with the



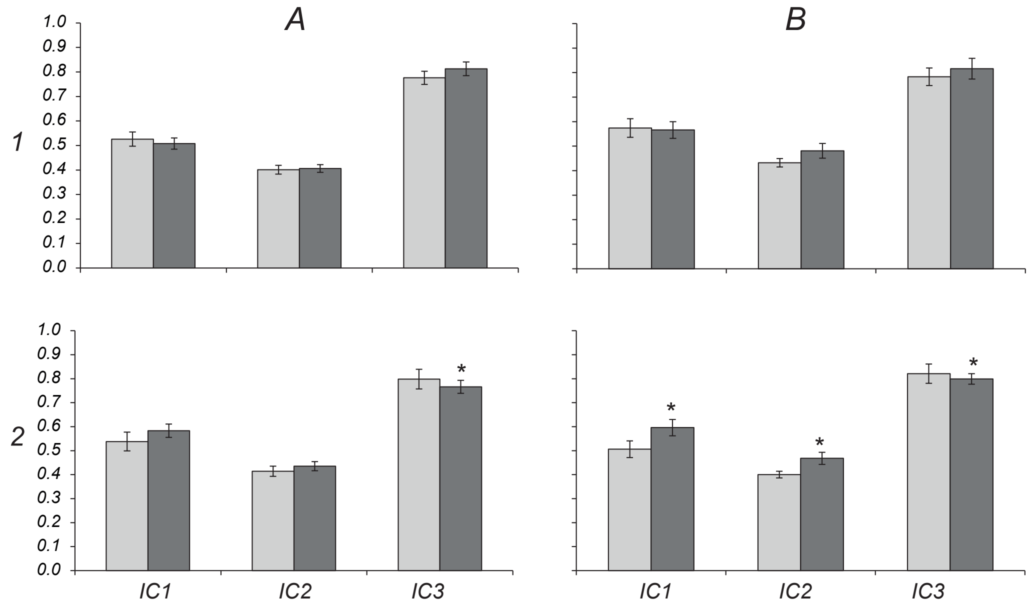
F i g. 3. Coefficients of intracortical interaction IC1–IC3 for oscillations of the alpha1 subrhythm in groups of the tested subjects. Indications are the same as in Fig. 1.



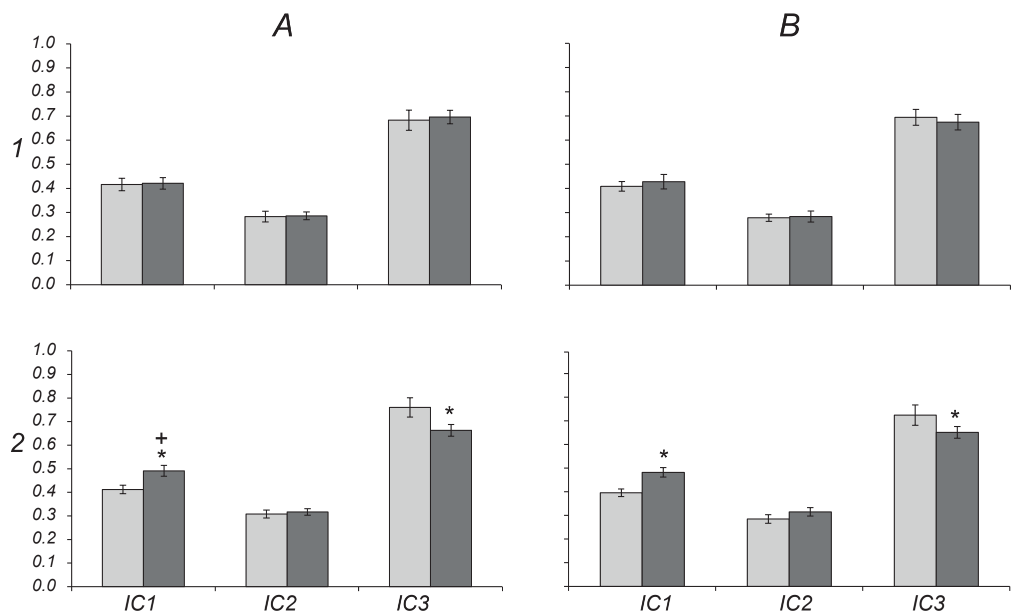
F i g. 4. Coefficients of intracortical interaction IC1–IC3 for oscillations of the alpha2 subrhythm in groups of the tested subjects. Indications are the same as in Fig. 1.

indices of productivity in the performance of the divergent test task. At the same time, values of definite ICs calculated for the periods of cognitive activity showed a certain specificity dependent on different levels of creativity of thinking in the groups of subjects. Such a situation was, however, observed only in tested men.

The mean intragroup values of IC1 in men with a high productivity of divergent thinking, when calculated for EEG oscillations of the delta, theta, alpha1, beta, and gamma frequency ranges and observed in the course of performance of the convergence-type test task, significantly exceeded the corresponding values in men with a low level of



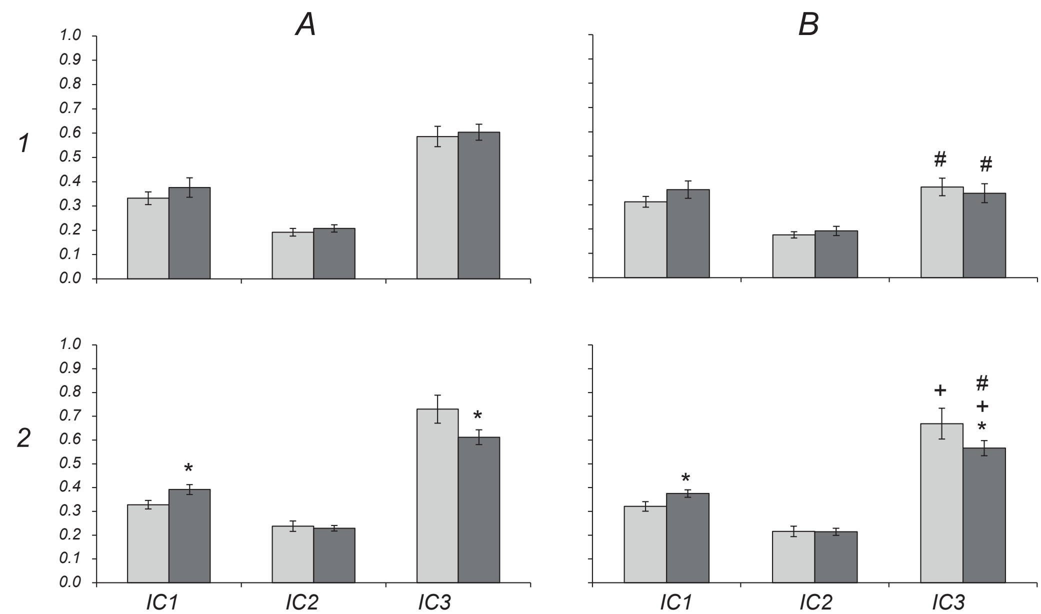
F i g. 5. Coefficients of intracortical interaction IC1–IC3 for oscillations of the alpha3 subrhythm in groups of the tested subjects. Indications are the same as in Fig. 1.



F i g. 6. Coefficients of intracortical interaction IC1–IC3 for oscillations of the beta rhythm in groups of the tested subjects. Indications are the same as in Fig. 1.

creativity (Figs. 1–3, 6, and 7, A2). For oscillations of the alpha2 and alpha3-subrhythms (Figs. 4 and 5, A2), we also observed an analogous trend, but the differences did not reach the level of significance. During the performance of the divergent test, mean values of the IC1 in men with high productivity of divergent thinking significantly exceeded the respective values in men with mostly convergent thinking in all frequency ranges of EEG activity (Figs. 1–7, B2).

The situation with the IC2 was largely similar to that described above. Mean IC2 values shown by men with high creativity of thinking in the course of realization of the convergent-type test task were significantly greater for oscillations of the delta, theta, alpha1, and alpha2 frequencies, as



F i g. 7. Coefficients of intracortical interaction IC1–IC3 for oscillations of the gamma rhythm in groups of the tested subjects. Indications are the same as in Fig. 1.

compared to the respective indices in low-creativity individuals. A similar but weak and insignificant trend was observed for alpha3 oscillations. Under conditions of the convergent task, values of the IC2 for beta and gamma oscillations demonstrated no intergroup differences. The pattern of IC2 values shown under conditions of divergent task performance was almost identical to the above described. These coefficients in men with the higher divergence of thinking significantly exceed the corresponding values in “low-creativity” men; this was observed for delta and theta activity and for the entire alpha rhythm (including the alpha3 subrange) and combined with the absence of any differences of IC2 values for high-frequency EEG components.

As to the patterns of the IC3 coefficient, values of which reflect, in some manner, the intensity of coherent relations between activities of neuronal systems of the posterior and anterior cortical regions, the situation was considerably dissimilar. For the theta rhythm, this coefficient during the performance of the divergent-type test task by men with high productivity of divergent thinking was significantly smaller than that in men with low productivity. A similar trend was observed for EEG oscillations of this range during the performance of the convergence test task, but the difference did not reach the level of significance (Fig. 2, A2, B2). The differences between IC3 values for high-frequency EEG components (beta and gamma oscillations) demonstrated the same direction and were significant. The respective IC3 values for both the above rhythms in men with high indices of the divergence of thinking were significantly smaller than the analogous values in men with low indices of this psychological feature (Figs. 6, 7, A2, B2).

The pattern of coefficients IC1–IC3 during the performance of test tasks of both types by women dramatically differed from that observed in men. In a great majority of cases, the values of these factors in the course of resolving both tasks showed no systematic intergroup differences. Almost all values of all three coefficients in women with different levels of divergent thinking were rather close to each other; their differences observed in some cases usually did not reach the level of statistical significance. Values of the IC3 for the delta range were an exception. In women with the high level of creativity, the mean of this coefficient significantly exceeded the respective index in women with low estimates of this property (Figs. 1–7, A1, B1).

Comparisons of the mean IC1–IC3 values in men and women belonging to similar groups according to the level of creativity of thinking did not show significant systematic intergroup differences for all analyzed EEG frequency ranges. Nearly the same can be stated when comparing the respective values of these coefficients in the same group obtained for the performance periods of the convergent and divergent tasks. Thus, the gender identity and the type of the executed tasks cannot be considered factors significantly affecting the calculated ICs for the anterior and posterior areas of the cortex. The same can be said with respect to the coefficient that characterizes interzonal communication (IC3).

Thus, analysis of the patterns of the generalized indices characterizing coherent interactions within the anterior and posterior neocortical parts and interzonal cohered interactions observed in the course of performance of two different-type cognitive tasks showed that men with the higher productivity of divergent thinking (higher creativity) more frequently demonstrate greater IC1s for oscillations of all EEG frequency ranges. Such men, as a rule, have greater IC2s for low- and mid-frequency EEG rhythms (delta, theta and alpha) and smaller IC3s for theta oscillations and high-frequency rhythms (beta and gamma). These features are largely invariant with respect to the type of cognitive tasks (convergent and divergent), which require the involvement of dissimilar resources of creativity of thinking. It is important to emphasize that such a pattern was typical only of tested men, i.e., this aspect showed a clear gender specificity.

At present, the problem of gender differences in the brain organization of cognitive functions is attracting considerable attention. Nowadays, it is not only the existence of specific forms of cognitive processes in men and women, which is a generally recognized fact. It was found that, in the case of identical (or very close) forms of behavior and results of cognitive activity, cerebral organization of the control of this phenomena can demonstrate significant sex-related differences from the neurophysiological, neurochemical, and even structural aspects [14, 15].

The identical (or nearly identical) effectiveness of mental activity can be achieved using a variety of mental strategies; different strategies should have different cerebral mechanisms providing control of the respective activity [16]. We believe that the observed specific pattern of the coefficients characterizing cerebral interactions under conditions of realization of cognitive test activity is related precisely to the fact that men and women use dissimilar mental strategies during the fulfillment of the divergence test tasks (and, perhaps, of tests of any type). Thus, such a pattern can, to a certain extent, serve as an EEG marker of the high productivity of divergent thinking, but only in men. A number of studies showed that the principles of selection of sensory and verbal information in men and women are markedly dissimilar. Most men rely, to a greater extent, on a self-determining mode and use impulsive/global strategies. Women largely prefer to base their behavior on adaptation to the existing notions with sequential processing of information and its interpretation (comprehension). For the formation of a decision, most women try to obtain maximally detailed accessible information [17–19]. It is obvious that such statements are based on statistical relations, and exceptions may be rather frequent. Self-reports of our tested subjects showed that women, in general, analyze the content of the tasks in more detail, isolate the most important part of such information, and then visualize the task. As for men, there was an impression that test tasks were in most cases evaluated in general and sometimes rather superficially. “Masculine” strategy was frequently based on the search of some ready schemes in memory and their generalized evaluation from the aspect of their applicability for solution of the given problem. Such cognitive strategies could, in a certain sense, be called stereotyped (routine). If such strategy provided a positive outcome several times, it began to be used in the future for resolving analogous tasks. A certain variant of intracortical interaction, which allowed the subject to realize such strategy with optimum (minimum) energy costs, began to be fixed.

It is believed that men with highly effective divergent thinking are characterized by stronger and more effective, on average, interaction of neuronal networks within the anterior (frontal) associative cortical regions. At the same time, interaction between the anterior and posterior associative regions (and the corresponding systems of attention) is somewhat limited in many cases. The values of IC3s for high-frequency EEG oscillations (beta and gamma) and (to some extent) for theta activity in “highly creative” men were significantly smaller, while IC3s for delta and alpha activity demonstrated no significant differences in men with high and low thinking creativity.

The frontal cortex, which includes the respective associative mechanisms, is considered the main cortical area that provides the descending (top-down) control and processing of information in the course of development of behavioral decisions. The frontal cortical areas are also responsible for selection of the variants of such decisions. The more intense interaction of neuronal networks within the anterior cortical parts is, probably, precisely the factor that determines the greater values of the IC1 coefficients in men with a higher efficiency of divergent thinking. This feature is, to a certain extent, typical of interaction within the posterior cortical areas, but such similarity, in this case, is only partial. Women probably possess, in general, more flexible mental strategies; the latter, in turn, are explained by the more variable neurophysiological mechanisms than those in men. It seems that precisely such variability determines the absence of clearly manifested differences between the levels and patterns of intracortical interactions in the course of cognitive activity of definite types evaluated in terms of coherence.

The idea that men and women perform cognitive operations with dissimilar degrees of interaction between different areas of the cerebral cortex has been expressed many times. It was believed [22] that specificities of the frequency/spatial functional organization of the cortex during cognitive activity of different types, which are typical of men and women and manifested when different information processing strategies are used, are related to the following fact. In men, the frontal system of attention is more important, while the respective functions in women are performed by the parietal system; the latter, in this case, closely interacts with the left-hemisphere part of the system of frontal control. Other authors [23] concluded that a dominating role of the right hemisphere is manifested under analogous conditions; interaction within the posterior cortical zones with a shift of the focus toward the right hemisphere is increased. At the same time, in women, the left hemisphere (in particular, the left-hemisphere temporal areas) plays the dominating role. According to these authors, such differences are associated with different strategies of performance of convergent cognitive tasks, namely, visual/spatial in men and mostly verbal in women. It was emphasized that, in the course of analysis of the EEG patterns during the process of creative thinking, it is necessary to pay attention not only to the peculiarities of lateralization of EEG activity, but also to the cooperation of the anterior (frontal) and posterior (parietal) cortical regions [24]. It is believed that, respectively, these sites are responsible for two separate functions of the creative process, "critical-initiating" and "search" ones. The parietal system is responsible for precisely the latter aspect of creativity; it provides generation of multiple ideas due to the existence of various visual, auditory, and symbolic associations. At the same time, the frontal system realizes the critical-initiating function and, according to the individual goals and interests, provides selection of the ideas coming from the parietal system, develops more prospective directions, and suppresses the directions evaluated as ineffective ones. Other authors also expressed views nearly similar to the above-mentioned ones [25]. They believed that the frontal cortical areas are able to establish extensive connections with "polymodal" and "supermodal" elements of the temporal and parietal areas, i.e., with the neuronal systems where information on special knowledge and skills is stored [26]. It was suggested [25] that precisely this mechanism can "switch on" divergent-type thinking; the latter can be inhibited and activated selectively, and this modulates the process of formation of alternative solutions. The results of studies of the spatial/frequency organization of EEG activity using the appropriate tests gave reasons to believe that memorization of semantically meaningful verbal information is realized in women with the involvement of variative polymodal strategies, while "narrower" and more specific strategies are used in men [22, 27].

The results of our study suggest that the high productivity of divergent thinking in men correlates with the greater intensity of neuronal interactions within networks of the anterior and posterior associative cortical areas and is accompanied by certain functional separation of these cortical regions from each other. Thus, specific patterns of integrated coherence indices for the "anterior associative," "posterior associative," and interzonal coherent connections in men can be interpreted as definite correlates of the high and low productivity of divergent thinking. In contrast, the respective peculiarities of the above-mentioned patterns are practically not observed in women. Our data confirm the existence of significant gender specificities of the interareal and intraareal coherent relations of EEG activity.

Acknowledgment. The authors are deeply grateful to Prof. D. A. Vasilenko for valuable critical remarks and comments that helped to significantly improve the quality of our paper.

All tested persons (students of the [1] Lesya Ukrainka Eastern European National University, Lutsk) were provided with all necessary detailed information with respect to the purpose and procedures of testing. All participants gave their preliminary written consent to be involved in the study. Thus, this study met the respective ethical principles expressed in the Helsinki Declaration (1964 and subsequent editions), which was confirmed by the Ethics Committee of the Lesya Ukrainka EENU.

The authors of this publication, I. Ya. Kotsan, N. O. Kozachuk, I. P. Kuznetsov, and A. I. Poruchynskii, confirm the absence of any conflict related to the commercial or financial problems, to the relations with organizations or persons, which could in any way be associated with the investigation, and to interrelations of the co-authors.

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