A STUDY OF THE CONNECTEDNESS AMONG DISTANT NEURONAL POPULATIONS IN THE HUMAN BRAIN DURING MENTAL ACTIVITY

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In this article, we present the results of a study of connectedness among distant neuronal populations in human deep-brain structures. The time characteristics involved and the stability of the connections between different neuronal populations during monotonous mental activity are discussed. We show that a stable connectedness does correlate with mental activity; however, the connections themselves do not correlate with one another. We also show that the individual connections, the elements of the system which make mental activity possible, can function with various degrees of rigidity or flexibility.

Key Words: Connectedness between neuronal populations, connections between populations, stability of connectedness, neuronal populations, correlates to activity, elements of a system, links in a system, activity-maintaining system.

Conditions providing for direct, multiple points of contact with the brain have now raised the study of the structural-functional and neurophysiological organization involved in the cerebral maintenance of human mental activity to a qualitatively new level. In particular, they allow us to analyze the space–time relationships between different areas of the brain. Investigations utilizing such multiple points of contact are based upon a systematic principle applicable to the operation of the brain. It can be assumed that, when performing any kind of concrete activity, a system is formed in the brain consisting of links (between neuronal regions) participating in the maintenance of the activity and a set of connections between the links. These links and connections can be rigid or flexible elements in the system [2-5]. Coordinated action within the system as a whole is possible only during fairly rapid and regular interaction between the links in the system. During the maintenance of simple types of activity, this interaction may operate according to the principle of the so-called trace lines. However, more complex and, especially, psychological activity cannot be maintained on this basis. It is impossible to imagine a situation in which connections between the links in a system would be established once and for all for nonstereotypic mental activity. It is absolutely necessary, especially for the complementarity of the linkages, that connections exist which change in time and space. Naturally, the question arises as to exactly which of these connections and which of their characteristics are continued through time and space. The problem can be surveyed from a physiological point of view; this approach includes data on characterizations of the dynamics of impulse activity. In this article, we are concerned with the problem of studying the actual connectedness between large (>10,000) numbers of neuronal regions during a process involving rapid, almost instantaneous processing of complex information. Different variants of correlational analysis are usually used for this purpose; however, when the problem is one of studying connections (and not relationships between activities in the various zones), it is expedient to use a method of analyzing coincidence functions between neuronal discharges. The present report makes use of this method to study the dynamics involved in connections between different neuronal areas of the brain during the maintenance of mental activity and to study the characteristics of these connections.

METHODS

Recordings of multicellular activity were gathered from deep brain structures (the striatopallidal system) of patients with Parkinson's disease implanted with intracerebral, long-term electrodes for therapeutic and diagnostic purposes. The parameters of the electrodes

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were determined, on one hand, by the necessity of realizing diagnostic and therapeutic electrical effects upon the brain with their aid and, on the other, by the necessity of monitoring the state of near-electrode zones in the brain after operations and during recovery periods. Therefore, the patients received implantations of 6 to 15 bundles (6 electrodes to a bundle) of gold electrodes in one or both hemispheres, according to the instructions of the medical doctor. The diameter of each electrode was ≈ 100 μm, and active surface area was on the order of 0.1 mm^2. The active surfaces of the electrodes within a bundle were situated at distances of 3 mm from one another. The system for designating the electrodes was as follows: the Roman numeral corresponds to the number of the bundle and the subscript corresponds to the number of the electrode in the bundle. For example, $XIII_2$ is the second electrode in the thirteenth bundle. The locations of the electrodes were decided upon prior to the operation and were then precisely located using x-ray data and data gathered during the course of therapeutic and diagnostic stimulations [1, 8]. The sizes of the active surfaces of the electrodes were within limits, which made recording of the signals possible. As a rule, only multicellular activity was recorded (under exceptional circumstances; however, we succeeded in isolating pulses from individual neurons). Therefore, the selection of a neuronal area for recording was predicated upon the presence within the area of high-amplitude (greater than 35 μV) multicellular activity with a satisfactory signal/noise ratio. In each patient used in our studies, such areas constituted approximately 10% of the total number of areas allowed for recording. Recordings of mental activity were carried out from the following neuronal regions of human deep brain structures located in the anterior ventral nucleus of the right thalamus and also in the left hemisphere in the putamen, and the ventral and dorsomedial nuclei: 1) IX_3 – Put(S); 2) VII_4 – VA(D); 3) VII_5 – VA(D); 4) XI_1 – MD(S); 5) XI_2 – MD(S); 6) $XIII_1$ – VL(S); 7) $XIII_2$ – VL(S). The work was carried out on an instrumentation-program complex developed jointly by the Department of Human Neurophysiology, Scientific-Research Institute of Experimental Medicine, Academy of Medical Sciences of the USSR, and the Laboratory for Modeling Mechanisms of Brain Activity at the Leningrad Scientific-Research Center, Academy of Sciences of the USSR.

Amplified multicellular activity was recorded on an 8-track magnetic (Sony) recorder. Eight-track amplitude discrimination of mental activity was then carried out with the goal of isolating patterns of neurons with impulses exceeding a certain predetermined threshold. All of the data presented in the article were obtained at a sampling level such that the average frequency of discharges was on the order of 30 pulses per sec in each channel. Following amplitude discrimination, pulse shaping of the signals into standard forms were carried out for each discharge in each channel. The shaped pulses from all of the channels were then fed into a "Plyurimat-C" computer. The technique used to enter the data into the computer has been described in detail in [6].

The analysis of the data entered into the computer was carried out using a search methodology for connections between distant neuronal populations in the brain [7]. It was noted in the description of the methodology that the approximation used here resulted in somewhat lower estimates for low frequencies. As a consequence of this, the number of connections obtained during the analysis was somewhat low. This shortcoming was surmounted by using an approximation which allowed us to obtain a more precise evaluation.

$$P = 1 - p\{\chi^2[2x]\} \geqslant \frac{2N_1N_2(2N - x + 1)}{2N^2 - N_1N_2}, \quad (1)$$

where x is the actual number of impulses following within a bin; N_1 is the number of pulses along channel 1; N_2 is the number of pulses along channel 2; and N is the number of bins. A schematic representation of the methodology is presented in Fig. 1.

In Fig. 1a, we have presented a representative sample illustrating the essentials involved in the analysis of the coincidence function. The moments when a pulse appears in a channel (a recording of multicellular activity from a certain neuronal area of the human brain) are noted by the straight, vertical dashes which parallel the axis of abscissas. A time scale with a fixed time window (the bin) has been simultaneously superimposed over all of the channel records. Two pulses from different channels are considered to coincide if they fall within the same bin (between the same fine vertical lines). The dimension of a bin is a parameter set by the investigator. For the statistical evaluation, the number of coinciding pulses (in terms of frequency) in the corresponding channels was set by the epoch of analysis (the time between the pair of thick vertical lines in Fig. 1a). The reliability of the difference between the actual number of coinciding pulses and the number which would be expected

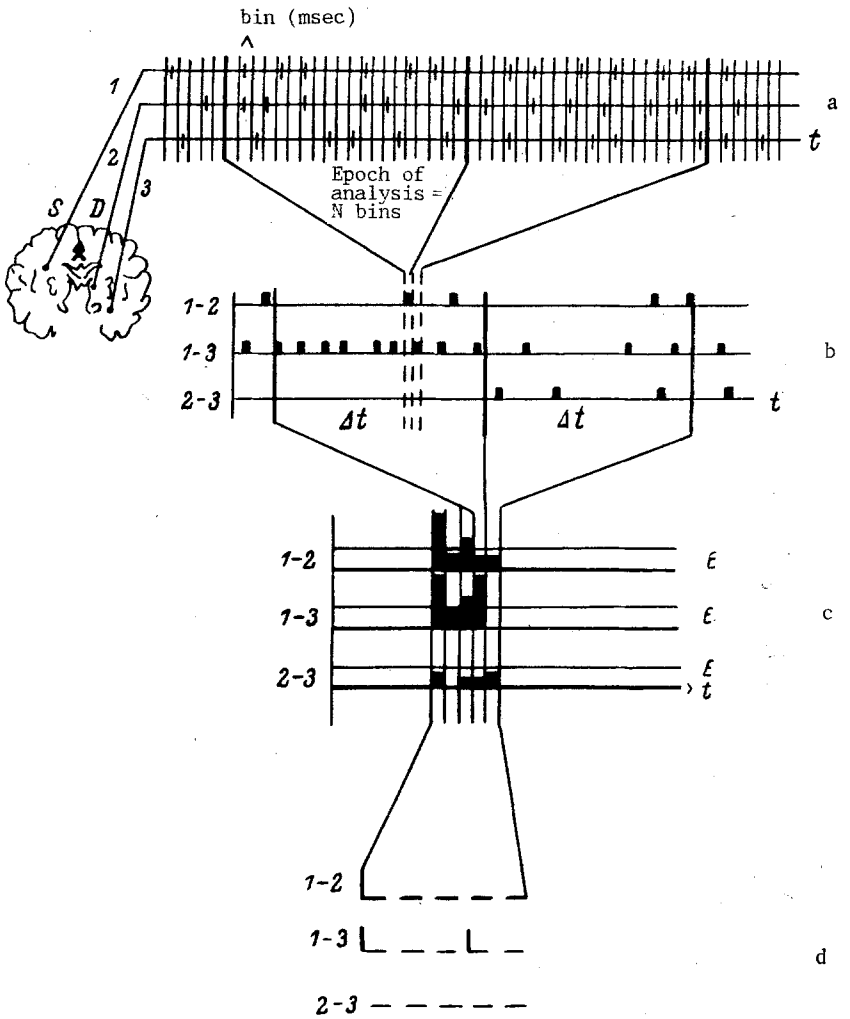

Fig. 1. Schematic representation of the search methodology for connections. a) Essentials in the analysis of the coincidence function; b) dynamics of the connections; c) total dynamics of the connections (for Δt); d) dynamics of the connectedness. The remaining features are explained in the text.

for two random, unconnected pulse trains of the same frequency was determined within the epoch of analysis. If the statistical estimate obtained exceeded the predetermined confidence level p = (0.975, 0.995), then we considered a connection to be activated between the two corresponding neuronal populations with this level of confidence. The estimates of coinciding pulses changed when the size of the bin was changed, and the sampling volume for the statistical evaluation of the coincidence function changed when the epoch of analysis was altered. By varying the size of the bin and the epoch of analysis, it is possible to find those sizes of bins and those durations of epochs at which the statistical evaluation of the coincidence function is maximal and exceeds a preset confidence p. Thus, we considered a connection between corresponding neuronal populations to be activated with a characteristic connection time τ = the duration of a bin and an activation time for the connection T = the duration of an epoch of analysis.

In Fig. 1b we have presented a representative example of the dynamics involved in the activation of connections between all possible pairs of neuronal populations. The activation of a connection with an actual T and τ is marked for each pair of units (thick vertical notches).

In Fig. 1c we have systematically laid out the dynamics of the total number of activated connections for an actual pair of neuronal populations over a time determined by a concrete type of activity, for example, for any phase of a test with duration Δt.

Figure 1d illustrates the results of a statistical evaluation of the numbers of activated connections, connections shown along with their dynamics in Fig. 1b, c over a time Δt.

We found it necessary to use a statistical evaluation because overshoots of the given confidence level p due to random causes were possible for a fairly large number of the observations.

The statistical evaluation of the number of actual connections observed allowed us to determine the connectedness involved, in the form of reliable deviations of the numbers obtained from the number E anticipated mathematically (Fig. 1c), during the operation of pairs of neuronal populations. A positive connectedness appeared as a reliably small number of connections. For example, one turn at proofreading samples lasts 150 sec. Three hundred evaluations of the χ^2 criterion with p = 0.025 were obtained during an analysis with T = 0.5 sec. In this case, seven occurrences of formally reliable overshoots of this level were obtained due to random causes. If twelve or more instances of overshoots of a given confidence level were obtained, the given pair of neuronal populations would have been considered positively connected at this level of confidence and, if three or less instances of overshoots were obtained, the given pair of neuronal populations would have been considered negatively related. From here on, a positive connectedness will be referred to simply as connectedness. Those pairs of neuronal populations which show connectedness (positive or negative) for all samples of the type of activity being investigated will be referred to as stably connected. It is impossible to speak of a stable connectedness in the background activity, since the background activity does not include monotypic, repeated test samples. For the background activity, it is thus only possible to give an evaluation of the connectedness or unconnectedness of pairs of neuronal populations over a certain time. Those pairs of neuronal populations which do not show a connectedness for even a single pair of types of activity investigated will be referred to as stably unconnected.

The analysis of the coincidence function was carried out on a "Plyurimat-C" computer with the aid of approximation (1) for the choices of parameters used in the analysis; the epochs of analysis equaled 1.5, 1.0, 0.5, and 0.25 sec, and the bins equaled 1, 2, 3, 4, and 5 msec.

As is evident from what has been presented above, the methodology employed does not give a very high time resolution. Since the average epoch of analysis used in the coincidence methodology is on the order of 1 sec, it is necessary to provide the patient with a fairly monotonous task in order to ensure that the subject's state does not change appreciably during an epoch of analysis. Monotonous tasks requiring constant attention were selected for this purpose. Each phase in the execution of these tasks takes a time on the order of 150 sec. This provides a fairly representative sample for the methodology used. Three types of widely known proofreading texts were presented.

1. A table consisting of broken rings possessing eight different orientations was presented to the patient on a screen. He was then asked to count the number of rings possessing a given orientation. The exposure time (approximately 150 sec) was selected so that the subject could not finish the counting within the time alloted. The subject related the results of his counting while a dot remained on the screen (for 3-5 sec). This task was repeated eight times. In the process, a specific state corresponding to a specific activity was formed and reinforced.

2. The patient was presented with the previous table (for a time on the order of 150 sec). Then, following the appearance of a dot (for 3-5 sec), a plot from a book by Bidstrup was presented for the same length of time alloted for the presentation of the table. The patient was given instructions beforehand to remember the plot. These types of test constructions were used for periodic, abrupt changes in activity, i.e., periodic disruptions of the functional structure of the activity.

3. A table similar to the one described above was presented; the table could contain one or two solid rings or no rings. The subject was asked to find a solid ring or indicate the absence of such a ring. This task differed from the first in that no counting was involved.

The physical characterizations of all of the slides (the dimensions, degrees of illumination) were approximately the same. The presentation was carried out automatically with the aid of a tachistoscope.

TABLE 1. Quantitative Characterization of the Stable Connectedness of Pairs of Neuronal Populations with Different Values of T and τ

Types of activity	T sec	τ msec	Stably connected	Stably unconnected	Unstably connected
Proofreading samples with counting	1.0	1	6	4	11
		2	1	1	19
		3	0	3	18
		4	0	6	15
		5	0	9	12
	1.5	1	5	3	13
		2	3	0	18
		3	0	2	19
		4	0	2	19
		5	0	7	14
	0.5	1	0	3	18
		2	0	9	12
		3	0	9	12
		4	0	14	7
		5	0	14	7
Proofreading samples without counting	1.0	1	6	3	12
		2	3	1	17
		3	1	3	17
		4	0	7	14
	1.5	1	7	3	11
		2	2	2	17
		3	1	5	15
	0.5	1	3	4	14
		2	0	3	18
		3	0	9	12
	0.25	1	2	4	15

			proof-reading	plot	proof-reading	plot	proof-reading	plot
Proofreading samples with counting plus plot recall	1.0	1	5	0	3	3	13	18
		2	0	0	5	6	16	15
		3	0	0	0	0	21	21
	1.5	1	3	2	8	6	10	14
		2	0	0	0	0	21	21
		3	0	0	0	0	21	21

RESULTS OF THE INVESTIGATION

Results according to the data of four investigations are presented here. The following types of activity were studied: 1) background activity, i.e., the absence of active goal-directed activity (tranquil wakefulness); 2) proofreading samples with counting; 3) proofreading samples without counting (searching of an unbroken ring); 4) proofreading samples with counting alternated with tests of plots.

As a result of the analysis, quantitative characterizations of the connectedness between neuronal populations within the specified set of neuronal populations were delineated for all types of activity studied.

Data on the numbers of connections and their parameters T and τ, both for all pairs which were involved in maintaining the type of activity studied in general and for specific pairs of neuronal populations stably connected during the maintenance of the types of activity studied, are summarized in Tables 1 and 2.

The number of stably connected pairs of neuronal populations (Table 1) during maintenance of monotonous activities with similar connection parameters for T = 1.5 and T = 1.0 sec proved to be almost identical for the investigations in which the proofreading samples were presented sequentially and the functional structure of the action was not disrupted.

When compared with cases in which the functional structure of the activity was preserved, the number of stably connected pairs of neuronal populations in investigations which included a disruption in the functional structure of the activity (proofreading samples alternating with plots) turned out to be somewhat smaller for T = 1 sec and was two times smaller for T = 1.5 sec. Only two pairs of neuronal populations showed stable connectedness during recall of a plot with T = 1.5 sec and τ = 1 msec.

TABLE 2. Connection Parameters T and τ for Stably Connected Pairs of Neuronal Areas during Monotonous Activity

Type of activity		Pairs of neuronal areas	Connectedness parameters T and τ			
			T = 1.5 sec and τ msec	T = 1 sec and τ msec	T = 0.5 sec and τ msec	T = 0.25 sec and τ msec
Proofreading with counting		IX_3—VII_4 [Put (S)—VA (D)]	1, 2	1	§	§
		IX_3—$XIII_2$ [Put (S)—VL (S)]	1, 2	1	§	§
		VII_4—XI_1 [VA (D)—MD (S)]	§	1	§	§
		VII_1—$XIII_2$ [VA (D)—VL (S)]	1	1	§	§
		XI_1—$XIII_2$ [MD (S)—VL (S)]	1	1	§	§
		$XIII_1$—$XIII_2$ [VL (S)—VL (S)]	1	1, 2	§	§
		IX_3—$XIII_1$ [Put (S)—VL (S)]	2	§	§	§
Proofreading without counting		VII_4—XI_1 [VA (D)—MD (S)]	1	1	§	§
		VII_4—XI_2 [VA (D)—MD (S)]	1	1	1	1
		VII_5—XI_2 [VA (D)—MD (S)]	1	2	§	§
		XI_1—XI_2 [MD (S)—MD (S)]	2, 3	1, 2, 3	1	§
		XI_1—$XIII_2$ [MD (S)—VL (S)]	1	1	§	§
		XI_2—$XIII_2$ [MD (S)—VL (S)]	2	1, 2	1	1
		$XIII_1$—$XIII_2$ [VL (S)—VL (S)]	§	1	§	§
		VII_4—$XIII_2$ [VA (D)—VL (S)]	1	§	§	§
Proofreading with counting plus plot recognition	K	IX_3—VII_4 [Put (S)—VA (D)]	1	1	§	§
		IX_3—$XIII_2$ [Put (S)—VL (S)]	§	1	§	§
		XI_1—XI_2 [MD (S)—MD (S)]	1	1	§	§
		XI_2—$XIII_2$ [MD (S)—VL (S)]	1	1	§	§
		$XIII_1$—$XIII_2$ [VL (S)—VL (S)]	§	1	§	§
	C	$XIII_1$—$XIII_2$ [VL (S)—VL (S)]	1	§	§	§
		XI_1—XI_2 [MD (S)—MD (S)]	1	§	§	§

Note. T and τ characteristics for which no corresponding pairs of neuronal populations were observed are denoted by the symbol §.

The numbers of neuronal populations stably connected at T = 0.5 and 0.25 sec, as is evident from Table 1, were small; such populations were characteristic only of proofreading samples which did not involve counting and which allowed the examinee to rapidly scan a table being presented in search for an easily recognizable sign.

As was noted above, the analysis was carried out for bins of 1-5 msec duration. However, as is evident from Table 1, stably connected pairs of neuronal populations with characteristic connection times τ greater than 3 msec were not discovered (for the set of neuronal areas investigated and with regard to the types of activities studied).

As is evident from Table 1, the number of neuronal areas stably unconnected during monotonous activity, regardless of whether a disruption in the functional structure of the activity occurred or not, was constant and equaled 3-4 for τ = 1 msec with the various values of T, except in the case of T = 1.5, when proofreading samples alternating with plot recall were used. In this case, the number of pairs of neuronal populations not stably interrelated equaled 8 during the proofreading tests and equaled 6 in the plot-recall tests, i.e., were two times greater. In this case, there was a smaller number of stably connected pairs.

In general, Table 1 shows that the maximum number of stably connected pairs of neuronal populations was observed for τ = 1 msec for all of the types of activity studied. The minimum number of stably unconnected pairs when the functional structure of the activity was preserved occurred for τ = 2 msec.

In Table 2 we show specific neuronal populations with corresponding characterizations of connectedness stably formed during specific types of activity. As is evident from the table, from 5 to 8 pairs of neuronal populations were stably interconnected (with different connectedness parameters) during monotonous activity. Pairs of neuronal populations existing both in a single population and pairs of neuronal populations existing in different populations prove to be stably interconnected. Stable connectedness basically occurred with the connection characterizations T = 1.0 and 1.5 sec and τ = 1 and 2 msec.

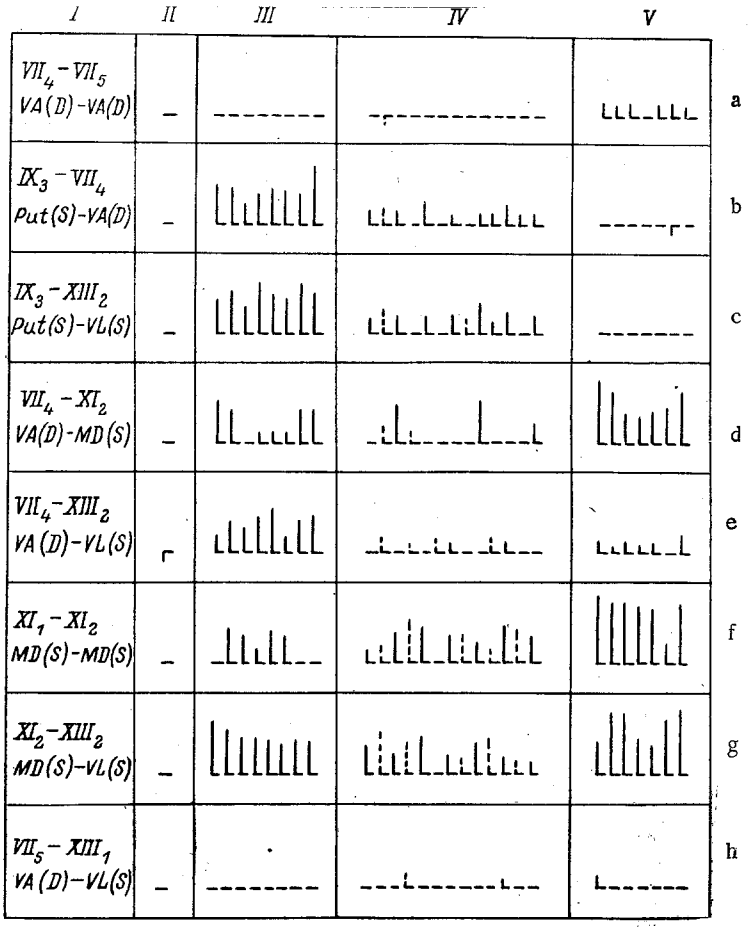

Fig. 2. Types of connectedness between distantly separated neuronal populations. I) Neuronal areas of the brain structures; II) background activity (the absence of goal-directed activity); III) proofreading tests involving counting; IV) proofreading tests involving counting alternating with a story; V) proofreading tests without counting. Along the horizontal: sequential trials are designated by dashes. Along the vertical: the size of the quantile (for $p \geq 0.975$). Calibration: along the vertical a quantile is 2.0. Solid vertical lines: proofreading tests; dashed lines: plot recall tests. Characterizations of the connections: T = 1 sec, τ = 1 msec.

Table 2 shows that there was a pair among the pairs of neuronal populations studied which was stably connected both during tranquil, monotonous activity (regardless of whether or not the functional structure of activity was disrupted or was nonexistent) with T = 1 sec and τ = 1 msec and during plot recall with T = 1.5 sec and τ = 1 msec; this was $XIII_1$ – $XIII_2$ [VL(S) – VL(S)]. A connectedness did not appear in the background activity of this pair for any of the values of T and τ analyzed. Thus, a stable connectedness during the maintenance of all of the types of activity studied was observed in one pair of neuronal populations which were anatomically close to one another.

On the other hand, two other anatomically close neuronal populations VII_4–VII_5 [VA(D)–VA(D)] did not show a stable connectedness during performance of the various types of activities for any of the values of T and τ. Thus, anatomical proximity of neuronal populations is not the cause of the stable connectedness in the functioning of the populations.

There were pairs among the neuronal populations which exhibited stable connectedness only during one type of activity: 1) during proofreading trials involving counting this was IX_3–XII_1 [Put(S)–VL(S)] with T = 1.5 and τ = 2 msec; 2) during proofreading trials without counting, this was VII_4–XI_2 [VA(D) – MD(S)] with T = 1.0, 0.5, and 0.25 sec and τ = 1 msec; VII_5–XI_2 [VA(D)–MD(S)] with T = 1.5 sec, τ = 1 msec and T = 1 sec, τ = 2 msec. Connected-

ness for individual values of T and τ was either not observed or a weak negative connectedness was observed for other T and τ. Thus, the enumerated pairs of neuronal populations from different hemispheres of the human brain were functionally connected during activity involving searching a table for a given sign.

Three pairs of neuronal populations showed stable connectedness during the subject's performance of monotonous activity when the functional structure of the activity was preserved, i.e., in all of the proofreading tests, both with counting and without counting, these pairs showed stable connectedness: VII_4–XI_1 [VA(D)–MD(S)] with T = 1 sec and τ = 1 msec; VII_4–$XIII_2$ [VA(D)–VL(S)] with T = 1.5 sec and τ = 1 msec; and XI_1–$XIII_2$ [MD(S)–VL(S)] with T = 1.5 and 1.0 sec and τ = 1 msec. Thus, the pairs of enumerated neuronal populations, both from a single hemisphere and from different hemispheres of the human brain, operate together during the maintenance of a search for signs.

Two pairs of neuronal populations were stably connected during the execution of the tests by the subject, regardless of whether the functional structure of the activity had been disturbed or not, i.e., in all proofreading tests with counting alternating with plot recall. These pairs were IX_3–VII_4 [Put(S)–VA(D)] with T = 1.0 and 1.5 sec and τ = 1 msec. Thus, these pairs of distant neuronal populations, including pairs from both a single hemisphere and from different hemispheres, functioned jointly during the maintenance of a search and counting of the signs used.

Let us now discuss the types of connectedness between several pairs of neuronal populations for the specific values T = 1.0 sec and τ = 1 msec during the subject's performance of the types of activity described above. First of all, it should be noted that connectedness are either absent or are weakly expressed in the background activity for all pairs of the neuronal populations between which stable connectedness can be observed during the subject's performance of any of the described tasks. The results of an analysis showing the most typical types of connectedness between actual pairs of neuronal populations are shown in Fig. 2. As is evident from the figure, pairs exist within the set of neuronal populations studied for which connectedness is not observed either in the background activity, i.e., during the absence of any goal-directed activity, or during one of the types of activity studied (Fig. 2h). Pairs of neuronal populations with connections of this type were both from the same hemisphere (XI_1–$XIII_1$ [MD(S)–VL(S)]) and from different hemispheres (VII_5–$XIII_1$ [VA(D)–VL(S)]).

A pair of neuronal populations XI_2–XII_2 [MD(S)–VL(S)] from one hemisphere showed an absence of connectedness in the background activity (Fig. 2g). The presence of a stable connectedness during proofreading tests, both with counting and without counting and regardless of whether the functional structure of the activity was disrupted or not, was characteristic of this same pair.

The results of the analysis for the remaining pairs of neuronal populations presented in the figure show that different variants of the proofreading tests can result in connectedness of different stabilities between the same pairs of neuronal populations.

Two pairs of populations XI_1–XI_2 [MD(S)–MD(S)] and $XIII_1$–$XIII_2$ [VL(S)–VL(S)] occurring in a single anatomical structure showed an absence of connectedness in the background activity. This pair showed no stable connectedness during proofreading tests with counting. The same proofreading tests alternating with plot-recall tests and proofreading tests without counting resulted in a stable connectedness.

The pairs of neuronal populations VII_4–$XIII_2$ [VA(D)–VL(S)] (Fig. 2e) from different anatomical structures and different hemispheres showed negative connectedness in the background activity (expressed in a fairly small number of connections). During proofreading tests involving counting, on the other hand, stable connectedness were manifest. In proofreading tests alternating with plot recall, a connectedness was observed only during two tests. Proofreading tests without counting resulted in connectedness in six out of seven tests but, in this case, the connectedness could not be considered stable.

The other pair of populations from different hemispheres VII_4–XI_2 [VA(D)–MD(S)] (Fig. 2d) was not connected in the background activity. No stable connectedness was manifest during proofreading tests with counting and proofreading tests alternating with plot recall. However, a stable connectedness was observed for this pair of neuronal populations during proofreading tests with counting. Connectedness were not observed in the background activity between two pairs of neuronal populations, one of which was from a single hemisphere (IX_3–$XIII_2$ [Put(S)–VL(S)] (Fig. 2c) and the other of which included different hemispheres ((IX_3–

VII_4 [Put(S)–VA(D)]) (Fig. 2b). Stable connectedness was manifest for both pairs of populations during proofreading tests with counting and proofreading tests alternating with plot recall. A stable connectedness was observed for the first pair during proofreading tests without counting. During almost all of the tests, no connectedness was observed for the pair of populations from different hemispheres. A negative connectedness was observed during only one test.

As is evident from Fig. 2a, connectedness was not observed in the background activity for a pair of neuronal populations VII_4–VII_5 [VA(D)–VA(D)] from a single anatomical structure. A stable connectedness was also absent for this pair of populations during proofreading tests with counting and proofreading tests alternating with plot recall. During proofreading tests without counting, however, connectedness was observed during six out of seven tests.

DISCUSSION OF RESULTS

In man, a dynamic system for maintaining a given type of behavior is formed in the brain during the execution of any activity. By elements of the system we understand both the set of neuronal populations – links in the system – included in maintaining the actual type of activity, and the connections between them. The elements and time characteristics of the connections within such a system are controlled by a neurophysiological apparatus determined by the phylogenetic and ontogenetic development, the peculiarities associated with the biochemical processes of the given individual, and the attempt of the individual to execute the given type of activity.

The clarification of the elements and time characteristics of this dynamic system allows us to first of all consider the connections as elements of the system and, on the basis of this, to distinguish connected neuronal populations as links in the system. If a connection is not found, however, this is still not an indication that a given neuronal population is not a link in the system, since the population in question could be connected with some other population in activity which was not recorded.

Studying the interrelationships involved in the operation of distantly separated neuronal populations on the basis of an analysis of the coincidence function allows us to locate and determine the time characteristics of the connections between the neuronal populations which are elements in the system formed in the brain for the maintenance of activity, including the type of activity under investigation.

The results presented above show that one can find elements of the dynamic system maintaining the activity which are flexible or rigid with respect to the dynamics associated with the connectedness of the neuronal populations.

It is best that we begin with the cases in which it is impossible to definitely judge the involvement of the neuronal populations (see Fig. 2h) in the maintenance of the types of activity being investigated by means of the dynamics associated with the connectedness of pairs of neuronal populations. In such cases, it can only be assumed that the given neuronal populations either are not links in the system during the process of maintaining the types of activity being studied or may be links in the system but are not directly connected with one another.

A stable connectedness during proofreading tests with counting was observed in the pair of neuronal populations VII_4–VII_5 [VA(D)–VA(D)]. This pair appeared as a rigid element in the system maintaining activity in the form of a search for an unbroken ring with $T = 1$ sec and $\tau = 1$ and 2 msec. On the other hand, an absence of connectedness was found for this pair during all of the other types of activity investigated and during the background activity. Thus, these anatomically nearby neuronal populations are, on the one hand, rigid elements in the system facilitating the proofreading of tests without counting and, on the other hand, are flexible links in the system maintaining psychological activity.

In analogy to the pair described, the pair of neuronal populations IX_3–VII_4 [Put(S)–VA(D)] from different hemispheres and different subcortical formations and the pair of populations IX_3–$XIII_2$ [Put(S)–VL(S)], from a single hemisphere and different subcortical formations (see Fig. 2b, c), displayed a stable interrelationship only during one type of activity (i.e., during proofreading tests with counting) but, in this case, a stable connectedness was manifest regardless of whether the functional structure was destroyed or was nonexistent). These pairs of neuronal populations appeared as rigid elements in a system for facilitating

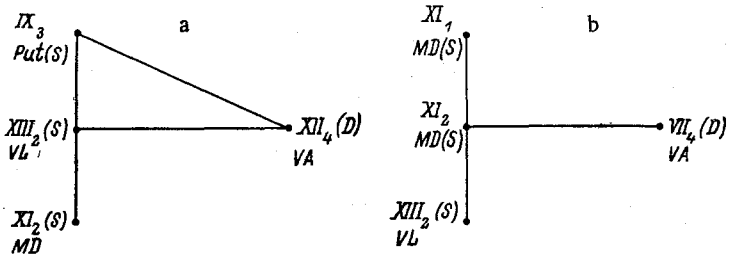

Fig. 3. Schematic representation of the elements of a system maintaining monotonous activity with the preservation of the functional structure of the activity (for T = 1 sec and τ = 1 msec). a) Proofreading tests with counting; b) without counting. The number of the electrode, corresponding to a zone of the brain (in analogy to Fig. 2), is designated by a subscript. These elements are the putamen, the dorsomedial and ventrolateral nuclei of the left thalamus, and also the anterior ventral nucleus of the right thalamus.

the proofreading of tests involving counting with T = 1 sec and τ = 1 msec. The absence of a connectedness in the background activity suggests that these two pairs of neuronal populations are rigid elements in the system for maintaining proofreading tests with counting, but the neuronal populations themselves are flexible links in the system maintaining psychological activity.

The neuronal population VII_4 from the anterior ventral nucleus of the right thalamus is a flexible link in the system maintaining psychological activity, but also forms rigid elements with its various links; the specific links formed depended upon the type of activity: VII_4–VII_5 and VII_4–XI_2 (Fig. 2a, d) were formed during proofreading tests without counting and VII_4–$XIII_2$ (Fig. 2e) was formed during proofreading tests with counting when the functional structure of the activity was preserved.

Analogously, the neuronal population $XIII_2$ from the ventrolateral nucleus of the left thalamus is a flexible link in the system maintaining psychological activity, but formed a rigid element with the neuronal area XI_2 (Fig. 2g) in the system maintaining goal-directed activity and the rigid elements $XIII_2$–VII_4 (Fig. 2e) in the system maintaining proofreading tests with counting when the functional structure of the activity was preserved and the rigid element $XIII_2$–XI_3 (Fig. 2c) regardless of whether the functional structure was destroyed or was nonexistent.

In this way, analytically suitable elements of systems maintaining the type of activity being studied can be isolated in the sets of neuronal populations. An arrangement of elements in a system maintaining monotonous activity and accompanied by a preservation of the functional structure of the activity is shown in Fig. 3 for T = 1 sec and τ = 1 msec.

Thus, formations of different systems (fragments of system) for maintaining different types of psychological activity have been uncovered during the investigation of the connectedness. Consequently, the connectedness can be assumed to be a correlate of the activity being investigated.

Let us now discuss the time characteristics T and τ. The present study shows that, during the maintenance of the types of activity described above, the activation of the connections does not occur at any time but at a time T lying between 0.25 and 1.5 sec. In between moments at which connections are activated ("conversations") a relatively long time occurs during which connections are absent between links in the system. The time T depends on the type of activity. No significant correlation between the magnitude of T and the distance between neuronal populations or their locations could be found.

The intransitivity of the connections should be noted here. The diagram of the interrelationship in Fig. 3a shows the existence of connections between neuronal populations VII_4, IX_3, and $XIII_2$, but the analysis of the moments of activation of the connections (the "communications") demonstrated statistically that each pair of neuronal populations was activated at different moments in time, i.e., each line was independent. Moreover, it is evident that connections VII_4–$XIII_2$ and $XIII_2$–XI_2 exist, but that there is no VII_4–XI_2.

The characteristic connection time τ determines how precise the coincidence of impulses is at the moment the activation of the connection. Table 1 shows that the greatest number of connections are characterized by a value of τ = 1 msec in the sets of neuronal populations studied.

An increase in the characteristic connection time coincides with a decrease in the number of connections, but consistent interrelationships are not observed for $\tau > 3$ msec. It should be noted that we considered the minimum characteristic time for a connection to be 1 msec, since 1 msec is the approximate duration of a neuronal impulse and it is therefore meaningless to consider coincidences with smaller τ.

The analysis of the τ characteristic allows us to draw some conclusions concerning the nature of the connections and why we are dealing with a direct connection per se and not a correlation or the connection through a third point.

First let us discuss why these are connections rather than correlations. A coincidence due to a correlation could exist for a structure expressed during the current of multicellular activity. Then, during a single synchronization at some moment in time, we could obtain a periodic positive or negative connectedness. A check of the recorded neuronal activity (that which we analyzed in the present article) using the methodology given in [9] shows an absence of structure in the currents of multicellular activity, i.e., the current of multicellular activity recorded during the investigations described above was random and coincidences due to correlations can be eliminated.

It might be suggested that these areas are synchronized to a third area. But then we would need to postulate that a third synchronized area which synchronizes each coincidence of impulse (neuronal discharge) exists for almost every pair of neuronal areas (since the selection of areas is dictated by the positioning of the electrodes, and connections exist for many pairs). While the synchronization need not be constant, it must be in operation during the execution of any activity. The situation in which a single correlation arises and further coincidences then occur due to some sort of rhythm existing in each channel is counterindicated by the absence of a structure associated with a current of multicellular activity. In such a case, if we assumed that a time on the order of 1 msec elapses during the passing of a single synapse, we will still need to assume (since τ = 1 msec) that the "synaptic distance" (number of synapses) from this third area to each member of our pair is identical. Taking into consideration that the electrodes are located in different subcortical formations and even in different hemispheres, the assumption of a third synchronizing area for each pair is an improbable one. Moreover, since τ = 1 msec, it is doubtful that these connections are realized as a result of the usual synaptic transmission. This follows also from a comparison of τ with the time for a synaptic relay; the time for a synaptic relay plus the discharge time itself is greater than 1 msec.

In conclusion, it should be noted that we have addressed ourselves only to investigation of connections determined by studying the function of the coincidence for neuronal impulses. We are not suggesting in any way that only such connections exist and are significant. Therefore, everything we have mentioned above has been in specific reference to the types of connections discussed above. We have, in addition, considered the investigation of connectedness in this article. The dynamics of the activation of the connections and the functional significance of the T and τ characteristics are also of interest and will be discussed in succeeding works.

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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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