FUNCTIONAL SIGNIFICANCE OF CORRELATION BETWEEN CORTICAL POTENTIALS

M. N. Livanov, V. A. Kravchenko,
and T. A. Korol'kova

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The problem of changes in synchronization of the brain potentials has long been a subject of interest to investigators. In recent years, a start has been made on the study of distant synchronization, as well as the familiar local synchronization expressed by an increase in the amplitudes of waves of the electroencephalogram (EEG). In distant synchronization, the potentials are similar in various spatially distant parts of the cortex.

To express the degree of synchronization of these processes quantitatively, a convenient method is to calculate the cross-correlation coefficients over a certain time interval (the analysis epoch). The use of this method with multichannel recording systems in different states of the organism has revealed a number of general rules connecting the functional state of the brain with the degree of synchronization of potentials from remote regions. Changes in distant synchronization have been demonstrated in human subjects during mental work, in various pathological states, and following administration of pharmacological agents, and in animals during adequate and inadequate stimulation of the brain, during the formation of conditioned reflexes, and so on [2, 7, 10-12]. The results of these investigations indicate the functional importance of distant synchronization of cortical potentials. However, before this significance can be measured, direct comparisons are necessary between the level of distant synchronization and an effector reaction. Such investigations became possible with the availability of the "Dnepr" controlling electronic computer, with direct operational coupling with the object and information feedback from it. The computer is not simply a machine calculating the experimental data, but an organic participant in the experiment. It was thus possible to perform an automatic electrophysiological experiment with feedback.

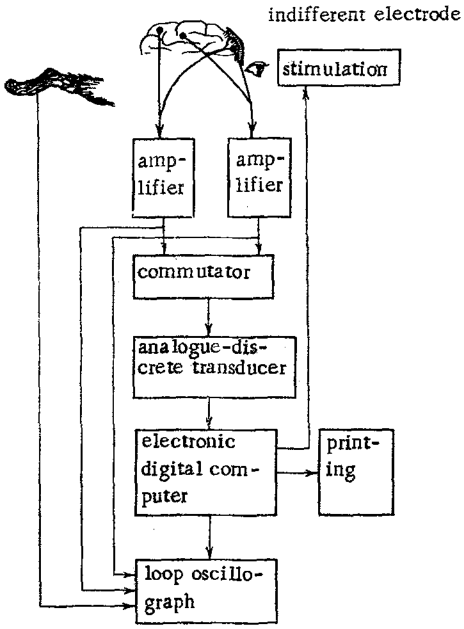

Fig. 1. Diagram of an automatic electrophysiological experiment with feedback.

In this particular investigation this method was used to study the significance of synchronization of potentials between the motor representation of a limb and the visual cortex in rabbits during performance of a motor response to flashes.

EXPERIMENTAL METHOD

Experiments were carried out on 14 rabbits. A description of the original form of the experiments is given in a paper by M. N. Livanov and co-workers [9]. The rabbit was scalped, and the area of motor representation of the hind limbs or fore-limbs was located through the bone by direct stimulation. Next, two EEGs were recorded simultaneously from this part of the sensorimotor cortex and from any point of the visual cortex, and after amplification and coding, they were fed into the calculating part of the computer. The computer continuously calculated the current coefficient of cross-correlation (frequency of interrogation 100 cps, analysis epoch 1.5 sec). At a definite level of synchronization of the potentials specified by the program, the computer switched on a flash of light and the

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TABLE 1. Number of Movements in Response to Flashes for Different Values of Coefficient of Cross-Correlation between Potentials of Motor Representation of Limbs and Visual Cortex

	High coefficient of correlation (from 0.8 to 1)			Low coefficient of correlation (from 0 to 0.2)		
	total number of stimuli applied	number of movements		total number of stimuli applied	number of movements	
		absolute	%		absolute	%
19 points (all points)	2,661	174	6.5±1	434	12	2.8±1
7 points ("active")	1,064	104	9.8±1	269	7	2.6±2
12 points (all the rest)	1,597	70	4.3±1	165	5	3.00±2

TABLE 2. Number of Movements in Response to Flashes for Different Values of Coefficient of Cross-Correlation Between Potentials of Motor Representation of Limb and Visual Area of Cortex

All 19 points	Coefficient of correlation					
	from + 0.8 to + 1.0			from + 0.2 to −0.2		
	total number of applications of stimulus	number of movements		total number of applications of stimulus	number of movements	
		absolute			absolute	
hind limb	380	104	27 ± 4	261	41	16 ± 4
forelimb	284	109	70 ± 4	580	174	30 ± 3

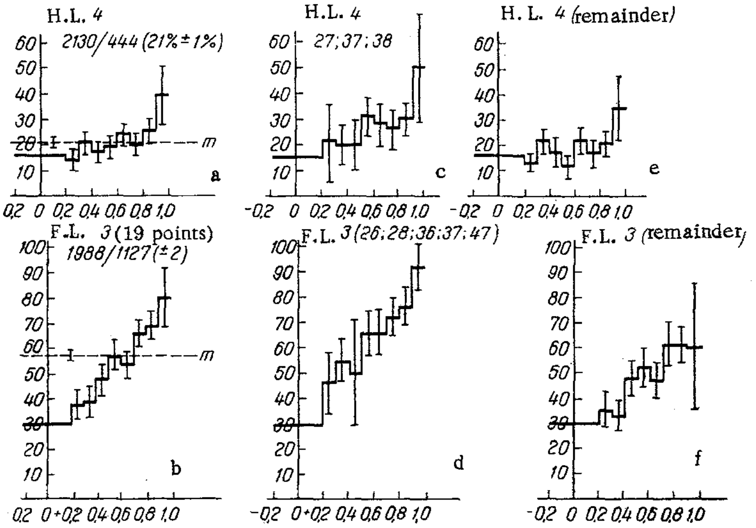

Fig. 2. Histograms showing relationship between number of movements in response to a flash and value of the coefficient of cross-correlation. a) Movements of hind limb. Histogram plotted for 2130 values of the coefficient of cross-correlation (for all 19 pairs of leads); b) movements of forelimb. Histogram plotted for 1988 values of the coefficient of cross-correlation (for all 19 pairs of leads); c) movements of hind limb. Histogram plotted for 678 values of the coefficient of cross-correlation (for 3 pairs of leads for "active" points indicated in Fig. 3); d) movements of hind limb. Histogram plotted for 1452 values of the coefficient of cross-correlation (for the remaining 16 pairs of leads); e) movements of forelimb. Histogram plotted for 642 values of the coefficient of cross-correlation (for 5 pairs of leads for "active" points indicated in Fig. 3); f) movements of forelimb. Histogram plotted for 1346 values of the coefficient of cross-correlation (for the remaining 14 pairs of leads). Abscissa represents values of coefficient of cross-correlation; ordinate represents number of response movements (in percent). Broken line represents assessment of mathematical expectancy of response reaction.

TABLE 3. Number of Movements in Response to Flashes with Different Degrees of Spatial Synchronization of Potentials between the Motor Representation of a Limb and the Visual Cortex

	Simultaneous high correlation (from 0.8 to 1.0) between potentials of motor area with potentials from points of visual cortex			
	with 5-4	with 3	with 2	with 1
total number of applications of stimulus	41	87	91	207
number of movements	20	32	33	33
percentage of response reactions	49 ± 13	37 ± 8	37 ± 8	16 ± 4

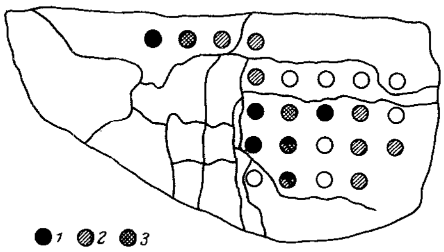

Fig. 3. Location of active points. Inside the outline of the hemisphere are shown the borders of the cytoarchitectonic zones as given by Rose (1931). The circles indicate the position of the electrodes. The motor representations of the limbs and corresponding points of the visual cortex ("active" points) are shaded identically. 1) Location of representation of forelimb; 2) location of representation of hind limb for some rabbits; 3) location of representation of hind limb for other rabbits. Unshaded circles –points of the cortex which are not "active" points for any limb representation.

instrument recording the animal's motor response (Fig. 1). The energy of the flash was 0.4 J, the distance to the eye 25 cm, and the light was scattered. Delay of the flash relative to the moment of actual existence of a particular coefficient of cross-correlation was less than the interval between two interrogations of the detectors (< 10 msec), i.e., it was practically instantaneous.

Study of the phenomenon by the use of two leads was not satisfactory because, while observing the behavior of synchronization of the potentials between the motor representation of the limb and one point in the visual cortex, it was impossible to know the state of synchronization of the potentials between the sensorimotor area and other parts of the visual cortex. Attempts were therefore made to increase the number of recording leads. The difficulty here is that only 10 msec (the interval between interrogations) is available to interrogate the detectors of the analogue-discrete transducer and to analyze the information obtained. Ability to do this is limited by the speed of response of the transducer (1 msec for each interrogation), the speed of response of the computer (10,000 operations per second), and the volume of operative memory (1500 numbers). By arranging the numerical material rationally and using shortened operations of multiplication and division, the number of channels could be increased to 6. The number of calculated coefficients of correlation was now equal to the number of combinations of 2 from 6, i.e., 15. This considerably increased the informative value of the experiments. As before, one pair of leads was used for tracking.

It was found that information could be obtained as regards both synchronization between visual points (4 or 5 at once) relative to motor points (1 or 2), and synchronization between different points within the visual area.

Two series of experiments were carried out. In series I the light was switched on when the coefficient of cross-correlation lay within the region $\rho \leq 0.2$ (absence of synchronization) or $\rho \geq 0.8$ (presence of synchronization).

In series II the light was switched on at different values of the coefficient of cross-correlation.

EXPERIMENTAL RESULTS AND DISCUSSION

In the experiments of series I, 4600 applications of flashes were analyzed for high and low values of the coefficient of cross-correlation. The results are given in Tables 1 and 2. In the first experiments the movements of the hind limb were recorded mechanographically. Table 1 shows that the difference between the number of responses for high and low coefficients of cross-correlation is significant. However, in these investigations only a small percentage of response reactions of flashes could be recorded. This was presumably because only powerful movements could be recorded mechanographically, and weak movements were not therefore taken into account. In addition, the interval between stimuli, determined by the duration of searching for $\rho \leq 0.2$ or $\rho \geq 0.8$, when testing a series of pairs of leads, was less than 30 sec. As a result of the frequent repetition of stimulation, the rabbit's response to flashes thus became extinguished.

In subsequent investigations electromyographic recording was used (leads taken from the flexors), enabling weak muscular contractions to be taken into account. In addition, before each search of the corresponding coefficient of correlation by a random number program, the waiting interval was determined, and the time between stimuli was thus random between limits of 30 sec and 5 min.

In these conditions the percentage of responses of the hind limb to flashes increased (Table 2). As before, the number of movements was greater with a high coefficient of cross-correlation, and the difference between the number of movements developing against a background of synchronization and in the absence of synchronization was significant. Still greater numbers were obtained when the movement of the forelimbs were recorded. The general rules discovered previously were confirmed in these experiments also.

When the coefficient of correlation was high, excitation evoked by the flashes thus traveled more easily to the motor centers than when the coefficient was low, i. e., synchronization of potentials between the motor and visual areas of the cortex plays an important role in the formation of movements in response to flashes.

To analyze the relationships between the coefficients of cross-correlation and the motor responses more accurately, obviously the relationship between the number of movements and intermediate values of the coefficient of cross-correlation had to be investigated, i.e., a curve of the relationship between the percentage of movements and values of this coefficient had to be plotted. This problem was examined in the experiments of series II.

The results obtained are given in Fig. 2 as histograms showing the relationship between the percentage of responses and the value of the coefficient of cross-correlation. It is clear from Fig. 2 that the relationship between the number of movements evoked by flashes and the coefficient of cross-correlation is linear: the higher the coefficient of correlation, the more frequent the movements. This linear relationship emphasizes yet again the functional importance of synchronization of potentials between the motor and visual areas of the cortex for the transfer of excitation from the visual analyzer to the motor system.

The existence of movements even in the absence of synchronization of the potentials complicates the elucidation of their cause. In these experimental conditions, this may mean either that synchronization with other points not tested at that particular moment was present in these cases, or that the reflex responses evoked by flashes were not of cortical origin, or finally, that a certain number of motor effects may also arise in the absence of synchronization of the cortical potentials. These suggestions do not conflict with modern views of the pathways of spread of excitation from the visual analyzer to the motor system [13, 14].

From the material at present available the results obtained can be assessed only in toto. Insufficient data have so far been obtained to assess the degree of synchronization of the potentials recorded by each pair of leads separately. However, from the tendency of the process it is possible even now to pick out a number of points in the visual cortex, the synchronization of whose potentials with the sensorimotor cortex was of great importance for the phenomenon observed. In the experiments of series I, for instance: for 7 of these "active" points the number of movements (hind limb, mechanographic recording; see Table 1) with a high coefficient of cross-correlation was 9.8%, whereas for the remaining 12 points it was 4.3%. Just as for the "active" points, as is clear from Fig. 2, c-f, the curve showing the relationship between the number of movements and the value of the coefficient of cross-correlation is steeper than that for "inactive" points.

What may determine the fact that synchronization of the potentials of individual points in the visual cortex with the potentials in the sensorimotor cortex varies in its functional importance?

The location of "active" points varies from one motor representation to another (Fig. 3). A common feature of these points is that those for the forelimb are situated more orally and those for the hind limb more caudally. Synchronization between the potentials of these points and those from the motor area indicates the selective link between these areas. However, another explanation is no less likely. The location of the "active" points may serve as the basis for a hypothesis explaining the predominant importance of synchronization of the potentials from these points with those of the sensorimotor cortex.

When the results of these experiments are analyzed from the standpoint of M. N. Zhadin's theoretical examination [5] it is clear that the coefficient of cross-correlation falls with an increase in the distance between the test points. This was seen particularly clearly in experiments when the computer was fed simultaneously with data characterizing 6 bioelectrical processes, and coefficients of cross-correlation were calculated between the motor center of the limb and 5 points of the visual cortex. This decrease of the coefficient of cross-correlation with distance does not follow precisely the same course as the decrease determined from the results of examination of the volume conductivity of the brain tissue. It may be concluded from these results that if the coefficient of cross-correlation at a distance point is high, it is also high at all intermediate points. The higher the coefficient of cross-correlation between potentials of the sensorimotor cortex and those from distant points, the wider the area of the cortex with synchronized activity.

Motor responses probably arise more easily when there is global synchronization of the cortical potentials. In this case the "active" points are those lying at the border of the region within which synchronization of the potentials is essential for movements to take place in response to photic stimulation.

It is clear from Table 3 that the greater the number of points in the visual cortex where the potentials are synchronized with the potentials of the motor representation of the limb, the more marked the phenomenon described above.

From this point of view some light can be shed on the mechanism of the stage of generalization of the conditioned reflex. It has been known for a long time that at the beginning of establishment of a conditioned reflex a sharp increase in synchronization of the cortical potentials takes place [1-4, 6, 8, 15, 16, 18]. V. D. Trush and T. I. Luchkova have now confirmed these data by calculating coefficients of cross-correlation between the motor center of the hind limb (to which the reinforcement was applied) and one of the points of the occipital region of the cortex in the course of the experiment.

After comparing the results described above with data given in the literature it may be postulated that an increase in the number of motor responses in the initial stage of generalization of a conditioned reflex is probably attributable to the fact that synchronization of the bioelectrical processes is established between the motor representation of the limb and numerous other areas of the cortex (in particular, the visual cortex). This must lead to an increase in number or to the appearance of motor reactions in response to the conditioned stimulus, and also to other stimuli of the same modality.

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