Modern Human Brain Neuroimaging Research: Analytical Assessment and Neurophysiological Mechanisms

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Abstract. This article aims at a comparative analysis of modern methods of neuroimaging for studying cognitive processes in clinical practice and psychophysiology, taking into account the original experience and data – event-related potentials (ERP), EEG, functional magnetic resonance imaging (fMRI) and positron emission tomography (PET). The main feature of neurophysiological diagnostics is time – spatial resolution. As a rule, these are fractions of a second (ERP), seconds (EEG), minutes (fMRI). Three groups of traditional neurophysiological research methods are used – EEG, fMRI and ERP based on the P300 component. The advantages of EEG include high temporal resolution, high gamma activity in the right temporal lobe, as an indicator of the mechanism of binding conscious information. The advantages of fMRI are high spatial resolution, increased blood flow in the right temporal lobe, hippocampus, striatum, medial prefrontal cortex, and dopamine region, nuclei adjacent to the ventral region. ERPs to some extent combine the advantages of EEG and fMRI. PET reflects the state of the brain over several days, which is associated with the life cycle of radioactive isotopes. The level of research corresponds to the entire brain. Microelectrodes, maps allow exploring individual neurons and nerve centers – nuclei.

Keywords: Event-related potentials · Brain computer interface · Positron emission tomography · fMRI

1 Introduction

What place among the methods of brain mapping do the approaches of clinical neurophysiology and applied psychophysiology take? If we represent on the abscissa the level of research from the whole brain to molecules, and along the ordinate, the time from milliseconds to several years, one can trace the inclusion of various neurophysiological mechanisms and their importance in the realization of mental functions (see Fig. 1). The main feature of neurophysiological diagnostics is time – spatial resolution. As a rule, these are fractions of a second (ERP), seconds (EEG, MEG), minutes (fMRI). Only positron emission tomography reflects the state of the brain over several days, which is

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associated with the life cycle of radioactive isotopes. The level of research corresponds to the entire brain. Microelectrodes, maps allow exploring individual neurons and nerve centers – nuclei [8, 15, 22].

Research in time	Research level				
	Brain	**Mapping**	**Layers/ Nuclei**	**Cells**	**Synapses**
Millisec/ sec	EEG, ERPs, MEG, ECoG		Neural activity		Biophysics
Sec/ hours	fMRI, USDG, NIRS, EDA		Vascular video microscopy		
Days	PET-scan		Angiography		Molecular biology
Years	CT, MRI				

Fig. 1. Comparative characteristics of neuroimaging methods (original).

2 Brain Evoked Potentials. Event-Related Potentials

In many psychophysiological studies carried out over the past 2–3 decades in various laboratories around the world, and during neurosurgical operations, the nature of the relationship between physiological and psychological indicators of perception had much in common. Early sensory evoked potentials (EP) waves (with PL up to 100 ms) show a high correlation with the indicator of sensory sensitivity, and the late ones, including the P300 wave, with the indicator of the decision criterion. Intermediate EP components with a PL of 100–200 ms revealed a double correlation – both with the sensitivity index and the decision criterion [10, 13].

Informative data on the essence of mental processes that make up the content of the third stage of perception were obtained in studies devoted to the analysis of the functional meaning and informational significance of the wave P300, which shows the highest correlation with the decision-making criterion. It should be said that over the past 40 years a phenomenon, and even a paradigm "P300", has formed in the literature, combining not one positive oscillation with a peak latency of 300 ms, but a whole complex of waves following this period of time [4, 9, 12, 14, 19].

Last two decades practical studies of the P300 ERP component have been associated with brain-computer interface (BCI) systems, which, in addition to solving physiological and psychological problems, have medical and social significance. Modern BCI systems can use a number of electrophysiological signals – visual EPs, slow cortical potentials, alpha and beta EEG rhythm, and the P300 component of evoked potentials [9]. The P_{300} has a number of interesting qualities that aid in the implementation of such systems. First, the wave is constantly detected and triggered in response to precise stimuli. And secondly, the signal to register the P_{300} can be triggered in almost all subjects with slight differences in measurement methods, which can help simplify the interface design and improve usability [11, 16, 17].

The bioelectrical activity of the brain is converted into an electrical signal during the signal acquisition phase [9]. Then the target user's desire is extracted from the signal. For this, various electrophysiological characteristics can be used. Algorithms developed specifically for BCIs interpret the desired action and send it to an output device, which can be a display with letters or targets (P_{300} speller, alphabet), a wheelchair or neuroprosthesis (for example, a robot arm) [14]. Feedback helps maintain and improve the accuracy and speed of communication/action. Finally, the P_{300} component of the evoked potentials can be used as control signals for the BCI. In a number of studies, P_{300} BCI systems have been tested in people with disabilities [9, 14].

Persons with disabilities can use the P300-based BCI for communication [9, 14]. The P300 spelling system (speller) is proposed, which allows subjects to transmit a sequence of letters to a computer. To create a "weird" oddball paradigm, a 6×6 matrix containing letters of the alphabet and numbers is displayed on the computer screen. A person can choose a specific sign by focusing attention on it. The BCI can also be used to drive a wheelchair. With the P300 BCI system, the user can select a destination in the menu by counting the number of flashes of the destination. Further, the wheelchair moves to the selected and desired destination along a predetermined path.

In addition to the wheelchair, an important application for people with severe motor impairments is the control of neuroprosthetic devices. BCIs can be used to control limb movements, for example, a robotic arm. It has been shown that BCIs based on the activity of cortical neurons are able to control three-dimensional movements of a robot arm [14]. In the future, P300-based BCI systems are being considered for controlling combat information posts and computer virtual games.

3 Functional Magnetic Resonance Imaging

One of the most interesting technologies of modern magnetic resonance imaging, fMRI, was developed in the early 1990s and was first used in human studies [16, 20]. fMRI is able to detect changes in blood flow volume and blood oxygen saturation level, morphologically and functionally associated with the identification of working neural networks, the formation of new and reconstruction of pre-existing neural ensembles (NE). The contrasting mechanism is based on the difference in the magnetic properties of oxyhemoglobin, which carries oxygen, and deoxyhemoglobin, which is formed at the places of its consumption. During the formation of an active NE in the first seconds, local energy consumption leads to an increase in the concentration of paramagnetic deoxyhemoglobin; then follows the reaction of the vascular system, which consists in increasing the regional blood supply and blood supply to the brain tissues (by regulating the volume and speed of blood flow). This leads to a sharp increase in the flow of blood saturated with diamagnetic oxyhemoglobin.

The sensitivity of fMRI to the physiological processes described above is due to the strong influence of the concentration of paramagnetic substances on the rate of magnetic relaxation of water protons. In the presence of a paramagnet, the rate of transverse relaxation T2* increases, which causes a decrease in the magnetic resonance signal and, conversely, a decrease in the level of deoxyhemoglobin leads to an increase in the signal [7, 17, 18].

Standard fMRI, where the physiological content is cognitive and sensorimotor processes, consists of several blocks, each of which includes a resting phase and an activation phase. The periods of activation and rest should not be too short, since the delay time of the vascular response is measured in several seconds, so the recommended duration of each phase is 20–30 s. The optimal sensitivity of the method is achieved by choosing such a phase duration at which the signal (BOLD) is in a state of dynamic equilibrium [15, 20].

Functional MRI can solve two classes of problems. Firstly, related to the measurement of hemodynamic response function (HRF) and, secondly, with the localization of the response. In the first case, the HRF is measured as a set of harmonic functions with a possible subsequent Fourier transform, while in the second case, the canonical form of the HRF is used, which empirically corresponds to most of the experimental data. The canonical HRF model is best applied in cases where it is necessary to determine when, where and in what sequence the evoked neuronal activity occurred. It may include delay and dispersion as degrees of freedom, allowing adaptation to regional or group characteristics [15, 20].

4 Positron Emission Tomography

The degree of preservation of human cognitive functions ranges from normal to profound disorders. Differential diagnosis of the causes of such disorders often causes difficulties in clinical practice. This was the basis for increasing neuroimaging research in this area. As is known, the most common causes of cognitive disorders are neurodegenerative disorders. Among the latter, Alzheimer's and Parkinson's diseases are the most common, accompanied by significant changes in brain metabolism with devastating neurological, clinical, as well as economic and social consequences. Such changes are visible using positron emission tomography (PET) already at the earliest stages [1–3, 5, 6].

Most often PET studies of the brain in neurodegenerative diseases were performed using [18F] fluorodeoxyglucose (FDG), an imaging radiopharmaceutical. Such data demonstrate diagnostic and prognostic value in assessing cognitive impairment and differential diagnosis of primary neurodegenerative disorders with different etiologies of changes in cognitive functions [5, 6, 8, 12, 21].

The intercortical interaction of the associative (frontal and parietal) parts of the brain, based on the analysis of PET data on glucose metabolism, was assessed by the activity of the line of cognitive systems. Four factor's systems were established: factor 1 – dorsal system of attention (voluntary attention), factor 2 – ventral system of attention (involuntary attention), factor 3 – system of the state of operational rest, and factor 4 - visual system in the norm and in patients with cognitive impairments of varying severity and pathology genesis were studied [12].

It has been established that the factor structure of regional levels of glucose metabolism in individuals with different nosologies, but without cognitive impairment, is stable in terms of the composition of factors. These factors in accordance with the affiliation of the areas of the brain experiencing the greatest load on the factor to one or another neuroanatomical system are explained.

The 1st factor includes the 8, 6 and 7 fields of Brodmann (the precentral cortex of the frontal lobes and the upper half of the parietal lobes of both cerebral hemispheres). The

2nd factor includes 46 and 40, 39 of Brodmann fields (the anterior third of the convexital part of the frontal lobes and the lower half of the parietal lobes). The 3rd factor includes the 23, 36, 29 and 30 Brodmann fields (the posterior cingulate gyrus). The 4th factor is the 17th Brodmann field (primary visual cortex).

Factor analysis found that in patients with Parkinson's disease without the syndrome of executive dysfunction, a factor structure with all 4 factors is formed. The same factor structure was recorded in patients of the control group and in healthy young patients. The syndrome of impaired executive functions and in the group of patients with vascular dementia is also accompanied by reorganization of the ventral and dorsal attention systems, as well as the system of operational rest (see Fig. 2) [12].

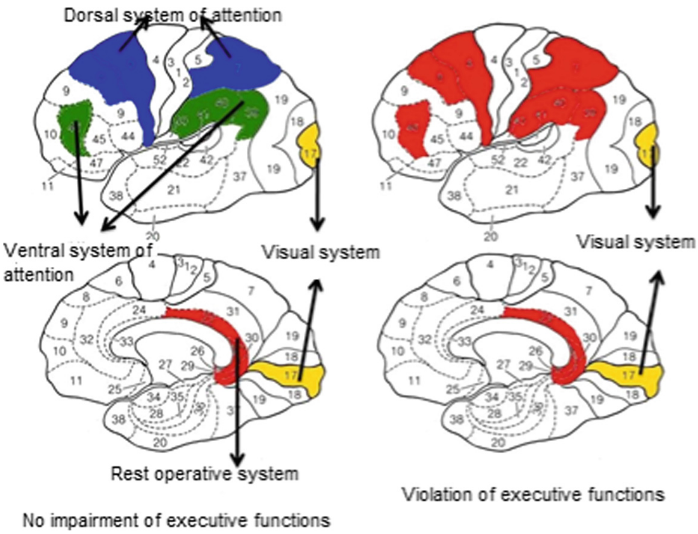

Fig. 2. Factor structure of self-organizing work of functional neuroanatomical systems for patients without impaired executive functions (left) and with syndrome of impaired executive functions, right (original).

5 Conclusion

In cognitive psychology, neurology, and psychiatry, the following areas and methods of studying perception are considered relevant (an example, the phenomenon of insight) (see Fig. 3). Three groups of traditional neurophysiological research methods are used - EEG, fMRI and ERP based on the P300 component. The advantages of EEG include high temporal resolution, high gamma activity in the right temporal lobe, as an indicator of the mechanism of binding conscious information, and the time interval of the insight effect (1310–560 ms) in terms of making an analytical decision. The advantages of fMRI are high spatial resolution, increased blood flow in the right temporal lobe, hippocampus (as a pleasure response), striatum, medial prefrontal cortex, and dopamine region, nuclei adjacent to the ventral region. ERPs to some extent combine the advantages of EEG and fMRI. ERPs have high spatial and temporal resolution, allow you to get closer to the problem of insight scaling. These results allow you to evaluate internal and external insight.

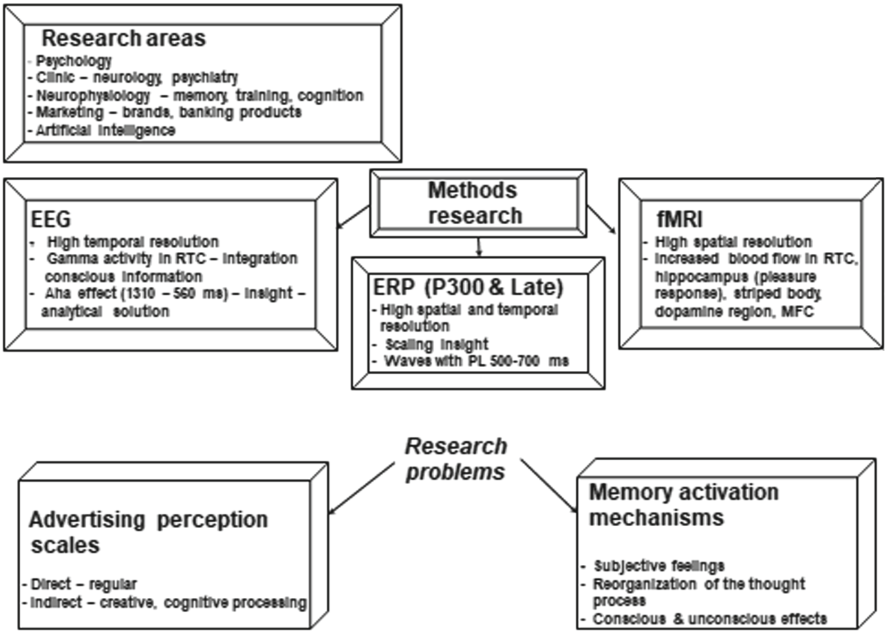

Fig. 3. The general directions, methods and problems of perception (insight) research (original).

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