Cognitive Science and Novel Medical Technologies

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Cognitive science is one of the fastest growing segments of modern interdisciplinary research into the functions of consciousness and into mechanisms implementing these functions in the brain. One of the impressive results of this research has been the emergence of novel scientific disciplines (cognitive ergonomics and neuroergonomics, neuroeconomics, neuromarketing) and a whole class of technological contributions in medicine and related life sciences. In this country, the relevant studies are conducted within the Interregional Association for Cognitive Studies (IACS) on the basis of the National Research Center "Kurchatov Institute". The authors of this article work in the Kurchatov Institute and represent the leadership of the IACS: Corresponding Member of the Russian Academy of Sciences B.M. Velichkovsky — the founder and first president of this Association (2006–2010) and V.L. Ushakov — the current president of IACS since 2018.

The article provides an overview of current neurocognitive research, combining fundamental issues with practical applications. The author describes the studies under way at the National Research Center "Kurchatov Institute" aimed at creating new types of human-machine interfaces, which are intended to replace the traditional graphic interfaces created for users at early stages of cognitive science. These studies concentrate on visual attention and voluntary oculomotor behavior. The methods and results of exploring the macroscale brain mechanisms are presented. Modern methods, such as ultrafast functional magnetic resonance imaging and dynamic causal modeling, allow one to non-invasively reconstruct the picture of cause-effect interactions in the human brain both at rest and at solving various tasks. Using these methods, it became possible, for the first time, to investigate the interaction between different brain mechanisms attributed to different evolutionary levels of its organization, namely, the oldest, old, new and newest cortex. An example of the first is the hippocampus, and that of the newest is the front-polar areas of the frontal lobes. As a result, new data on the asymmetry of the human brain in health and disease were obtained, indicating the importance of the interhemispheric asymmetry and the right hemisphere dominance over the effective (cause-effect) connections during normal functioning of the brain and consciousness at rest. The authors emphasize that the macroscale organization can and should be studied in the context of molecular mechanisms of the respective neural networks in the human brain.

The expression of protein-encoding genes in the frontal-polar regions of the cortex is presented. In this study, the right-sided dominance was also found but this time regarding the number of expressed genes associated with the risk of schizophrenia. However, no association with major neurodegenerative diseases was found.

Diagnosis of consciousness has always played an important role in medicine. To date, a communicative contact with the patient remains the main test of the consciousness integrity. Along with that, the significance of objective methods is growing. There are arguments that the modeling of consciousness and the respective implementation are the most important factors of further progress in the area of cognitive technologies and machine "intelligence".

Key words: consciousness; cognitive technologies; cognitive interfaces; active vision; effective brain connections; hippocampus; frontal lobes; hemisphere asymmetry; artificial intelligence.

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> Measure what is measurable, and make measurable what is not so.
> *Galileo Galilei*

Nowadays cognitive science represents the latest attempts to better understand how the brain and consciousness work. The history of such attempts goes back several centuries. In the second half of the XVI century, the progress in physics, and then in other natural sciences, was associated with the elimination of all mental concepts from the scientific lexicon. However, in the next century, Descartes restored the sphere of mental (*Res Cogitans*) to the level comparable to physical phenomena and processes (*Res Extensa*), emphasizing the primary belonging of this sphere to human beings (*Cogito ergo sum*). Moreover, based on Aristotle's early ideas and his own anatomical observations, Descartes suggested the importance of unpaired brain structures for the implementation of higher cognitive functions, such as thinking and reflexive consciousness [1]. Being the first and the current presidents of the Interregional Association for Cognitive Studies (IACS), we are confident that cognitive science is not only an area of basic research, but it also demonstrates an ever-expanding range of practical applications. Various scientific disciplines contribute — by methods, tools or models — to these processes, as reflected in the well-known acronym "NBICS-convergence"[1].

Spectrum of cognitive technologies

In this summary article and the upcoming series of publications, we will be primarily interested in practical applications of cognitive research. The most ambitious task in this area is the scientific understanding of consciousness. Over the past two or three decades, many important advances in the study of consciousness have occurred, but perhaps the most important feature is their practical significance. This applies to both the sensory and the effective aspects of consciousness, i.e. to the understanding of both "phenomenal clarity" of perceived contents, and of the so-called agentity — the subjective freedom to choose the decisions [2]. In ergonomics, the reflexive assessment of the workplace and the work tools (usability of such tools) came to the fore. In economics, the market success and the effectiveness of financial investments turned out to be largely dependent on psychological aberrations of consciousness, "cognitive illusions" [3]. Individual and social consciousness has become the focus of political technologies using the power of modern media to influence the people's minds.

The neurocognitive revolution has also become involved in the above areas, which resulted in the emergence of new disciplines: e.g., neuroergonomics, neuroeconomics, and neuromarketing. Several neurocognitive and behavioral methods are developing in the direction of more and more effective technologies of explication of individual knowledge and consciousness content — *mind and brain reading* [4]. A special task is the scientific identification of hidden knowledge and attempts of deception in socially significant situations. The "inner theater" of our consciousness often includes several actors. Thus, we notice that we are conducting an internal dialogue with ourselves or someone else, we look at ourselves by the eyes of others, evaluate others depending on how they evaluate us, try to imagine how we would act being "in the shoes" of another person or how another person would have behaved in our situation. Inter-subjectivity of consciousness is studied by social neurosciences, in particular, by their branches aiming at cross-cultural and ethno-psychological research (*cultural neuroscience*).

An example of applied research at the junction of several areas of cognitive science is the article of V.E. Karpov and his colleagues about the robotic wheelchair for the disabled. The main features of this device are the use of a multi-level management architecture, a psychologically sound programming language, and finally, multimodal human-computer interfaces. Historically, the development of these interfaces has become the very first task of applied cognitive research. In this area, a significant success was achieved with the replacement of traditional command line interfaces with graphical user interfaces at the turn of the 1990s. This progress was based on the proved concept of significantly greater memory efficiency of graphic images ("icons") as compared with memorization of verbal material, including the names of the simplest computer operations. However, by now, such interfaces have lost a considerable part of their attractiveness. At present, a major challenge is to create interfaces that react flexibly to the current attention of the user, his/her knowledge, interests and intentions [5].

Cognitive interfaces for human-machine interaction

The development of automation has not yet excluded the man from most technological processes; and for technologies focused on the human being, this goal is not achievable in principle. Those are, for example, the means of supporting patients with severe impairments of speech and movement, up to the syndrome of deafferentation (*locked-in syndrome*). About 30 years ago, the first reports on this and related subjects appeared in the literature. Those early attempts initiated

[1]A good illustration of this point is the name of the Kurchatov NBICS-complex of nature-associated technologies, where the capital letters denote nanotechnologies, biotechnologies, information technologies, as well as cognitive and social sciences.

the use of brain electrophysiological signals (electro- and magnetic encephalography — EEG/MEG), eye movements (eye tracking) and other unusual channels for communication purposes. Today it is one of the fastest growing areas of science and technology. In 2003, the Neuropsychology journal published a two-page letter that a patient with deafferentation syndrome wrote for six months. A few years later, another patient with the same condition, using the brain–computer interface (BCI), was able not only to communicate with the relatives but also to manage a small laboratory via e-mail [6]. Today, the simplest versions of such interfaces designed for computer games can be found on the market, and their cost is affordable to most users.

The BCI consists of a device for recording brain signals and a computer equipped with software that, in a close to real-time mode, analyzes the signals and recognizes patterns related to certain commands. When such patterns are detected, the BCI sends a respective command to the computer or a computer-controlled technical device [7, 8]. This type of interaction with the BCI differs from the training methods based on the biofeedback, in which an individual is tasked to maximize certain indicators of brain activity or keep them in a certain range of values [9]. In the latter case, the result of brain signal processing via the biofeedback is used only to inform the individual, while in the BCI the actions are carried out either in a virtual or in a real physical environment. This principle imposes strict requirements on computational algorithms and their software implementation: they must determine the user's intention as accurately as possible in the real-time mode using a small data volume. Due to that complexity, the rapid development of BCI technology began only in the XXI century.

Among the most promising medical as well as operational applications is the development of multimodal eye–brain–computer interfaces (EBCIs) developed at the National Research Center "Kurchatov Institute" [10, 11]. They make it possible to identify the signs of arbitrary intent in EEG/MEG signals and eye movements, transforming the intention into the movements of robotic devices. Notably, in the general scientific context, the solution to this problem was bequeathed to us by the question of Descartes "How does the thought of a hand raise a hand?". This problem was once classified by the founder of electrophysiology, Emil du Bois-Reymond, as of the category "We do not know and we will never know". Yet the solutions to this very problem do exist in our time thanks to the use of eye tracking and methods of electrophysiology. The high efficiency of the EBCIs is due to the basic principle they are built upon, which copies the architecture of the biological visual system, as well as the mammalian visual attention: i.e., the separation of two systems (or two "streams") of information processing related either to localization (the question "Where?") or the identification of objects (the question "What?").

Brain mechanisms of active vision

Modern neurocognitive studies suggest that each cognitive process involves not one but several spatially distributed functional zones combined into macroscale neural networks [12, 13]. In this respect, the mechanisms of active vision are no exception. Since this modality is central for all higher primates and humans, it earns special attention all over the world. As early as 1947, a Soviet scientist, the founder of the "physiology of activity" N.A. Bernstein proposed the existence of two autonomous mechanisms in the evolutionary hierarchy of brain structures, namely the levels of "spatial field" and "objective action" [14]. Only decades later, two types of visual perception mechanisms, functionally similar to those of Bernstein, were described; they were called the dorsal and ventral streams of information processing [15, 16]. These two brain mechanisms are believed to function for solving problems of localization and identification, which constitute the basis of the EBCIs architecture.

In this section of our review, we are talking about active vision because without oculomotor activity the visual perception is impossible [17]. But if the afferent mechanisms of vision have a dual character, then, a similar separation may be possible for the efferent mechanisms of vision manifested in eye movements? Indeed, studies show that the separation of two visual systems corroborate with the existence of two different classes of eye movements that are manifested in ambient and focal visual fixations [18, 19]. The ambient fixations have a relatively short duration and occur mainly at the beginning of acquaintance with a new spatial scene in the context of high-amplitude saccades. The focal fixations last longer, they are part of the short-amplitude saccades and centered on the objects rather than on the gaps between them.

The interrelation between the parameters of fixations and the type of visual information processing is highly important. Practically, by observing the patterns of the driver's eyes movements, it is possible to determine (with a high degree of probability) whether he/she can identify a dangerous situation in his/her field of vision or at this moment the driver is in the ambient perception (attention) mode, and, therefore, the control over the vehicle should be immediately transferred to the artificial intelligence systems [20].

The role of these mechanisms of perception and attention is still debatable. Generally speaking, the decisive role of the dorsal and ventral flows can be assumed. However, a direct experimental verification of this assumption proved difficult. The EEG method is not sufficiently accurate in terms of spatial mapping, while the main tool of modern neurocognitive studies, functional magnetic resonance imaging (fMRI), has a too low temporal resolution to be related to visual fixations rapidly replacing each other. Moreover, in a recent study, the transcranial Doppler sonography was used to measure the blood flow into the left and right hemispheres of a subject analyzing complex images [21]. The results showed that in the first 1–2 s into the image presentation, when the visual fixations were dominated by the ambient processing, the right hemisphere worked more intensively. Then, along with the increasing number of focal fixations, the hemispheric asymmetry of the blood flow leveled off or shifted to the left.

Currently, there are two hypotheses explaining the change in the eye movement mode in the process of free image viewing. The first one, which we proposed over 15 years ago, explains this phenomenon by the changing interactions between the dorsal and ventral information processing flows. The second hypothesis [21] attributes this observation to the differences between the hemispheres. Using a unique combination of ultrafast fMRI scanning with the fixation-based event-related (FIBER) method, we were able, for the first time, to analyze the brain function in term of ambient and focal visual fixations while the subject was freely viewing complex images [22]. Unexpectedly, the results confirmed both abovementioned hypotheses. In line with our early proposal, the ambient visual fixations are accompanied by activation of the classical structures associated with the dorsal flow, and the focal fixations — with the ventral flows. At the same time, the second hypothesis also proved to be correct: the activated structures of the dorsal flow were localized in the right hemisphere and those of the ventral flow — mainly albeit not exclusively in the left hemisphere.

The asymmetry of the human brain in health and disease

The data described in the previous section seem to speak about some important principle of the human brain functioning. The rapid global adaptation to a new situation is driven by the right hemisphere mechanisms associated not only with the dorsal stream mechanisms located in the neocortex but also with the much older evolutionary parts of the brain, to which the dorsal pathway eventually descends. In this respect, the most relevant formation is the hippocampus — the paired structure of archicortex, the oldest cortical part of the brain[2]. As the brain becomes adapted to the situation, the additional processing (previously developed and more routine) begins functioning. The latter include speech algorithms mainly associated with the left hemisphere. Such transitions, as shown by the dynamic balance of ambient and focal processing modes, can occur in a subsecond pace.

The use of novel neurocognitive approaches allowed us to describe, for the first time, the interaction between the hippocampus and other areas of the human brain [23]. The essence of our research was to study the effective (cause-effect) connections of the left and right hippocampi with the main structures of the so-called default mode network. This network maintains the brain work in the basic for human consciousness state of wakeful rest; structurally, this network encompasses the medial prefrontal cortex, the posterior cingulate gyrus, and the inferior parietal cortex of left (LIPC) and right (RIPC) hemispheres. The last two structures combine the intermodal (visual, auditory, vestibular and tactile) information about the contralateral half of the spatial environment: LIPC — about the right half-space, and RIPC — about the left half-space.

A group of 30 healthy right-handed subjects were asked to record their fMRI data at rest. To calculate the effective connections of the brain, a mathematical method of spectral dynamic causal modeling was used. After testing the predictive power of >3000 quantitative models, a pronounced asymmetry in the functions of the left and right hippocampi was revealed; that was unknown from animal experiments. Although these structures are both very active, the right hippocampus has a unique quality: it receives information from the both intermodal centers, LIPC and RIPC. This is the basis for the integral view of the environment. The left hippocampus, in contrast, is associated only with the LIPC, therefore its “knowledge” of the surrounding is limited to the right half-space. Such lateralization of effective connections explains one of the most frequent disorders of consciousness found in patients with right hemisphere lesions, namely, the left-sided hemineglect. As a rule, injuries of the left hemisphere do not lead to a similar loss of perception of the right half of the environment.

The following study extended this analysis to the interactions between different evolutionary levels of the human brain, i.e. the oldest, old, new and newest cortex [24]. By the “newest cortex” we mean the frontopolar regions of the frontal lobes (which are the fastest growing regions in anthropogenesis), or the Brodmann left and right areas (BA10). It turned out that the right-sided lateralization of the causal connections at rest is a rather general rule of intra- and inter-level interactions. In addition, there was a trend to control the evolutionary older structures by the newer ones. The only exception was the right hippocampus; its ascending influence on the newer structures, including the frontal polar cortex, was found. We have now completed a study on the interrelations between the abovementioned brain structures in patients with schizophrenia [25]. One principle result of this new study is that in these patients, we found no evidence of the right-sided lateralization of causal connections known from the norm. The

[2]Hippocampus attracts close attention of scientists because of its role in the processes of episodic memorization and space orientation. For their study on the hippocampal neurons in rats as the basis of the “cognitive map” of the environment, John O’Keefe, May-Britt Moser, and Edvard I. Moser received the Nobel Prize in Physiology or Medicine in 2014.

result is obviously clinically relevant, as it confirms the importance of interhemispheric asymmetry in the normal functioning of the human brain and consciousness.

Instead of conclusion: consciousness and artificial intelligence

Our article presents an overview of current neurocognitive studies that address fundamental issues and their practical applications in medicine and related fields. Due to the limited volume of this publication, we were able to discuss only the studies concerning macroscale mechanisms and processes in the brain[3]. The similarly intense cognitive studies are conducted in the area of "wet neurophysiology" (for example, the search for early immunological markers of neurodegenerative disorders of cognitive functions) [28]. Moreover, there is evidence indicating an interrelation between the macro-scale organization and the molecular machinery in the respective parts of the human brain. For example, our team recently tested the expression of protein-encoding genes in the front-polar regions of the human frontal cortex [29]. These results also showed the right-sided dominance, but this time — at the level of gene expression. Notably, these genes were implicated in the risk of schizophrenia but not in the risk of major neurodegenerative diseases. In the future, we can expect the identification of molecular mechanisms of consciousness.

Diagnosis of consciousness has always played an important role in medicine. To date, communicative contacts with the patient remain the major test of the consciousness integrity. At the same time, the significance of objective methods combining cognitive neuroscience data and mathematical models is growing. An example of this trend is the implementation of the integrative information theory [30], in which consciousness is viewed as a unified subjectively self-perceptible matter. This view of consciousness was expressed using a quantitative coefficient assessing the combinatorial complexity of brain responses to transcranial magnetic stimulation. This coefficient helps discern between the states of clear consciousness, sleep with eye movements, sleep without eye movements, anesthesia, and coma [31]. The accuracy of this quantitative diagnosis could be significantly improved if our data on the effective human brain connectome were considered.

Descartes was the first to suggest the connection between reflexive thinking and some unpaired organ (*sensus communis*), which he, however, localized incredibly low in terms of subsequent evolutionary ideas — in the midbrain structures. The discoveries of the left-sided asymmetry of the speech function in the XIX century, and (already in our time) the numerous forms of right hemisphere lateralization, allow us, while preserving the logic of Aristotle and Descartes, to seek a location of such an interface in other brain structures. To us, the most likely structure, at the moment, seems to be the right hippocampus [24, 32]. Notably, just a few months after our latest publication, the results of an extensive analysis of the functional connections of the default mode network were published. That study also revealed an unusual variety of connections of the right hippocampus as compared to its twin-structure in the left hemisphere [12].

The breakthrough area of technological development today is machine learning. Using the "deep learning" algorithms of artificial neural networks with intermediate layers and high-performance graphics processors, it becomes possible to solve tasks like speech recognition, computer vision and machine translation that remained unsolved for decades. In games with a fixed set of rules, machines are already demonstrating superhuman abilities, which are rapidly progressing with the growth of computer power. Despite these impressive successes, the current generation of software products still lacks the flexibility and ability to work in the new environment, which is characteristic of human intelligence. Thus, although the AlphaGO program recently succeeded in beating the world champion of the Go game, the machine needed to screen about 100 million game situations, while the champion himself apparently relied on the experience of less than 50 thousand game scenarios [33].

These differences between machine and man are qualitative, and not just quantitative. A player of average qualification is able to start playing according to *ad hoc* rules and under unusual conditions — e.g., with a board of a different size or shape (for example, representing the Mobius tape). Such unusual conditions block the "machine intelligence", and the blocking can only be overcome by efforts of highly skilled programmers and a new phase of continuous learning. Flexibility and ability to work in new conditions is part of the constitutive properties of consciousness that determine the creative potential of human thinking. Modeling of consciousness and its respective implementation are, therefore, the most important conditions for further progress in cognitive technologies and machine "intelligence". In other words, in those areas where this did not happen earlier, the problem of consciousness begins to take a central position as the biggest problem of science and its practical applications.

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[3]Even within this area of research, we had to abandon the discussion on some important issues, such as the neuro-linguistic mapping of the semantics and syntax of the Russian language [26] and the development of new methods of neuroimaging [27].

and schizophrenia; No.18-00-00569, Model of fixation in incubation of creative problem solving).

Conflicts of interest. The authors have no conflicts of interest to disclose.

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