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DECISION MAKING AND THE BRAIN: NEUROLOGISTS' VIEW

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ABSTRACT

The article reflects the fact, that concepts like decision making and free will have entered the field of cognitive neuroscience towards the end of 20th century. It gives an overview of brain structures involved in decision making and the concept of free will; and presenting the results of clinical observations and new methods (functional neuroimaging, electrophysiology) it postulates possible mechanisms of these processes. We give a review of the neuroanatomy, specially discussing those parts of the brain important to the present topic, because the process of decision making is dependent on deep subcortical as well as superficial cortical structures. Dopamine has a central role in the in process of reward related behaviour and hedonism. A list of brain structures, related to dopamine action, is also given. The article especially concentrates on the Single Photon Emission Computer Tomography studies in patients with Parkinson's disease (neuroimaging), as well as to the studies concerning the Readiness Potential and Endogeneous Potential P300 (electrophysiology). In the end, we discuss the volition, whose functional anatomy overlaps with the functional anatomy of free will and decision making processes.

KEY WORDS

cognitive neuroscience, brain, decision making, free will, electrophysiology, functional imaging, dopamine

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ANATOMICAL BASICS OF THE NERVOUS SYSTEM

From the non-dualistic perspective decision making is a brain process. Basic knowledge of the anatomy and physiology of the central nervous system is crucial for comprehension of the neurological substrate of decision making.

The nervous system is divided anatomically into central nervous system and peripheral nervous system. The peripheral nervous system consists of the cranial nerves and spinal nerves. The central nervous system is made up of the spinal cord, brainstem, diencephalon and telencephalon. The brainstem is comprised of three areas: the medulla oblongata, the pons and the midbrain (mesencephalon).

The telencephalon consists of two cerebral hemispheres. These include superficial grey matter of the cerebral cortex (neurones), the white matter (axons) beneath it, which interconnects distinct parts of the nervous system and the deep nuclei of the basal ganglia. (Fig. 6). Each of the hemispheres is divided into four separate lobes: frontal, parietal, temporal and occipital. In the centro–medial region is the limbic system, which comprises parts of frontal, temporal and parietal lobe and is crucial for the emotional processes and memory. Important structures in the limbic system are the cingulate gyrus, hippocampus, septum and amygdala.

The diencephalon consists of the thalamus (Fig. 1), the hypothalamus (the structure below the thalamus) and the epithalamus (the structure above the thalamus), which includes the pineal (glandula pinealis) and habenula.

The brainstem is the connection between the spinal cord, the cerebellum and the cerebrum. The nuclei of the cranial nerves III through XII are located in the brainstem along with long sensory and motor tracts that pass between the brain and the spinal cord. On the dorsal part of the midbrain there are the superior and inferior colliculi. The inferior collicus is part of the hearing pathway and the superior colliculus is important in the visual pathway. On the base of the midbrain is a functional part of the basal ganglia – the substantia nigra with cells that produce dopamine and give rise to fibers that project to the caudate nucleus and to the putamen. These fibers make up the nigrostriatal pathway (connection of the substantia nigra and basal ganglia). Mesocortical and mesolimbic pathway connect the surrounding structures in the midbrain with the frontal and limbic lobe respectively (Fig. 4).

The cerebellum (Fig. 5) overlies the pons and medulla and is separated from them by the cavity of the fourth ventricle. Phylogenetically it is divided into older median and younger lateral part. The cerebellum is involved in the control and integration of motor functions that determines coordination, balance and gait. Accumulating evidence suggests that the cerebellum also plays a role in affective and higher cognitive functions.

Physiologically, the nervous system can be divided into somatic and visceral (autonomic) divisions. The somatic nervous system deals with contraction of striated muscle and the sensations of the skin (pain, touch, temperature), the innervations of muscles and joint capsules (proprioception), and the reception of sensations remote to the body by way of special senses (taste, smell, hearing). The somatic nervous system senses and controls our interaction with the environment external to the body. The automatic nervous system controls the tone of the smooth muscles and the secretions of glands. It senses and controls the condition of the internal environment.

Wakefulness, alertness, arousal and decision processes are strongly dependent on circular connections between cerebral cortex, subcortical structures like basal ganglia, thalamus and

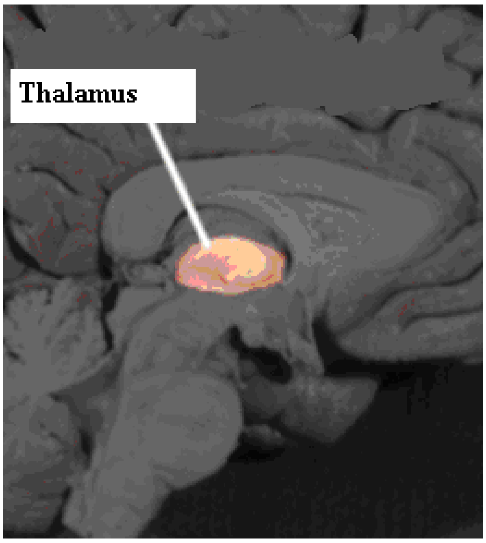

Figure 1. Thalamus.

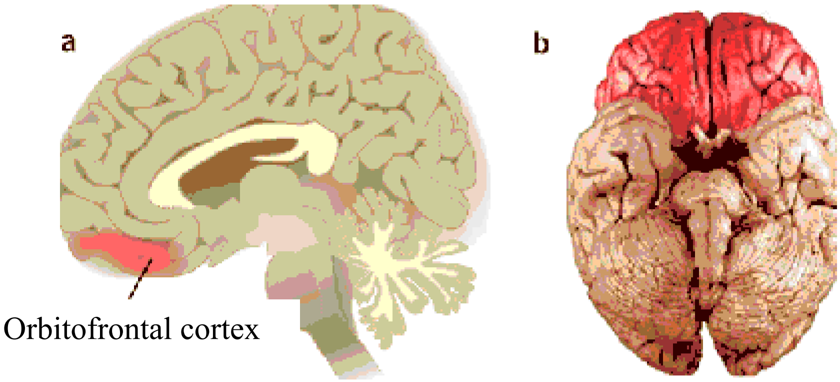

Figure 2. Orbitofrontal cortex.

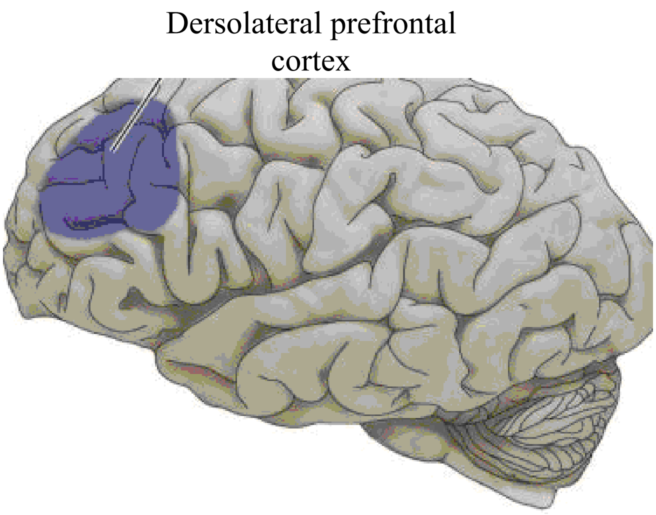

Figure 3. Dorsolateral prefrontal cortex.

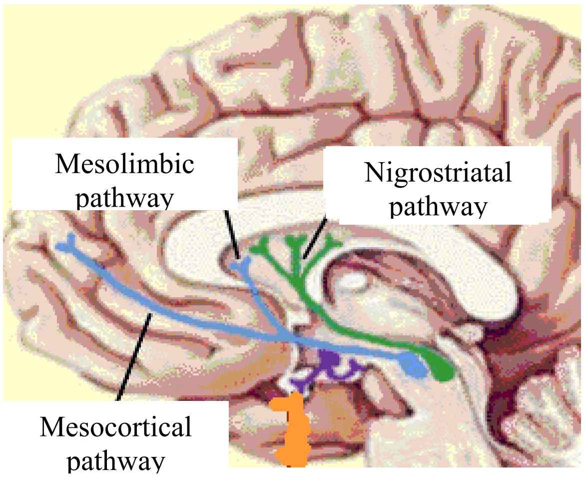

Figure 4. Mesocortical, mesolimbic in nigrostriatal pathway.

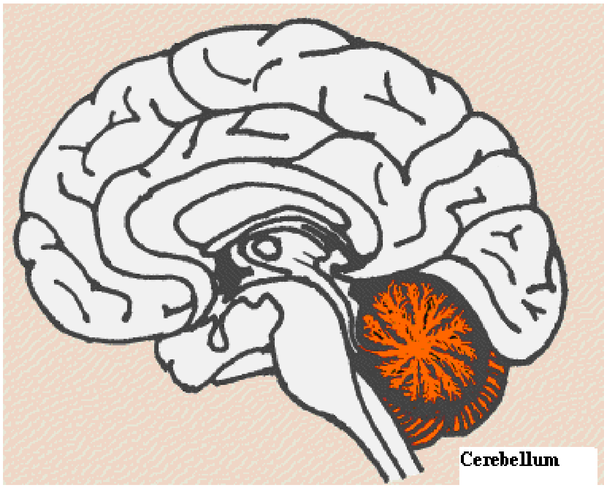

Figure 5. Cerebellum.

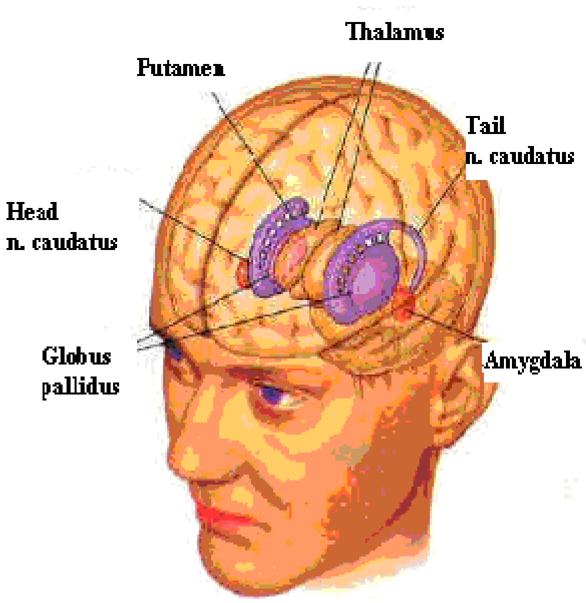

Figure 6. Basal ganglia.

frontal cortex where the programmes and decisions finally transform into acts; these connections are called cortico-subcortico-frontal pathways.

These connections are anatomical substrate for understanding the relationship between behaviour such as decision making and the brain. There are five pathways (loops), transferring either limbic, motor or cognitive information, following the same principle: the information from various parts of cortex converge to basal ganglia, from there to the nuclei of the thalamus and finally to different parts of frontal cortex [1].

The process of decision making is dependent on deep subcortical as well as superficial cortical structures. Among these are very important structures involved in process of reward related behaviour and hedonism.

Midbrain (mesencephalon): structures with predominance of dopamine as a neurotransmiter;

- substantia nigra
- ventral tegmental area
- mesolimbic pathway
- mesocortical pathway

- basal ganglia
  - ventral striatum (nucleus accumbens)
  - dorsal striatum
- limbic system (cingulate gyrus, hippocampus, septum, amygdala)
- prefrontal cortex
  - ventromedial and orbitofrontal prefrontal cortex
  - dorsolateral prefrontal cortex

These anatomical structures represent the basics for the process of decision making, which is the result of critical reasoning of possible multiple options and response choices, outcomes (reward/penalty) depending on motivational status.

ABOUT DECISION MAKING AND DECISIONS

Free and conscious decision making, if at all existent, is one the most complex presentations of human behaviour. Process of decision making was frequently explored from the philosophical and psychological aspect, but remains poorly studied topic in neuroscience. Research focused on the brain basis of process of decision making and acts of decision are only recent. The approach and topics vary, some scientists study simple, elementary physiological processes, i.e. decision making for wrist flexion, other researchers focus on complex moral, social and economical aspects of decisions. The study of the process of decision making in healthy and “normal” brain is very important for understanding the underlying mechanisms in healthy people as well as for understanding and treatment of neurological disorders with affected decision making i.e. Parkinson’s disease.

Neuroscience needs an operational definition of decision making (as a process) and decision (as an action). One of the possible definitions of decision making determines three conditions:

1. at least two different options should be available,
2. each possible choice offers certain outcome expectation,
3. possible outcomes can be evaluated.

There is wide spectrum of possible neurological studies on decision making:

- electrophysiological recording from one cell (information on decision making process on the level of one neuron, temporal discrimination of the method being approximately 1 millisecond, little localisation data),
- electrophysiological recording from several points on the scalp (electroencephalography (EEG), event related potentials, EEG coherence –information on decision making process on the level of systems),
- study of molecular mechanisms,
- study of neurotransmitter and pharmacological mechanisms,
- functional imaging methods (Functional Magnetic Resonance Imaging – fMRI, Single Photon Emission Computer Tomography – SPECT, Positron Emission Tomography – PET) – imaging of the structures involved in reward related behaviour and decision making, good localization but poor temporal discrimination – approximately 1s),
- clinical studies of neurological patients,
- studies of primates.

The process of decision making can be divided according to the level of awareness:

- decision making without awareness,
- decision making with partial awareness,
- decision making with full awareness.

According to the phenomenological complexity we can describe two distinct decision making processes which compete for the control over the final decision and act:

- simple, fast, perceptive-motor processes, evolutionally older, similarity with animals, process in sensory- motor parts ob the brain, non dependent on prefrontal lobe,
- complex, slower, reflexive cognitive-social processes with elements of self-awareness, evolutionally younger, dependent on frontal lobe , limited with working memory capacity, correlation with general intelligence quotient).

It is thought that there is anatomical separation of the decision making process for

- pleasant stimuli,
- aversive and painful stimuli.

FROM REWARD TO DECISION

The core of the decision making is motivational evaluation of the reward, risk or penalty related to certain decision. This motivational rewarding aspect is extremely important in the evolution since it allows the development of the behaviour pattern for successful survival. It is a basis for several cognitive processes (i.e. learning) and is developed in the brain of human and primates as a distinct system. The main biochemical role in this system has neurotransmitter dopamine.

Central components of the rewarding system are in the limic-cortico-subcortico-frontal loop: dopaminergic neurons in the mesencephalon, ventral striatum and ventral pallidum, anterior cingulate gyrus, prefrontal cortex (especially orbitofrontal part) and amygdala. Limbic and all other loops follow the somatotopic organisation through the whole pathway in a distinct and occasionally convergent course therefore operating in parallel and integrative manner [2]. Information about the possible reward or penalty enters from the limbic into the relevant motor and cognitive loops and allows preparation of the appropriate motor and cognitive plans leading to the final decision.

Distinct parts of the limbic cortico-subcortico-frontal loop represent different aspects of the rewarding behaviour: anterior cingulate gyrus and orbitofrontal cortex are active in the prediction of a mistake in the rewarding process, evaluation and choosing among current and long term benefit; cells in the ventral parts of the basal ganglia (striatum and pallidum) respond to expectation and detection of the reward. Disturbance in dopaminergic and opioid transmission in ventral stiatum (accumbens) in rats caused compulsive decision making exclusively for the reward – food and pharmacological substances [3], which defines accumbens as a very "hedonistic" structure. Mogenson [4] suggests that the nucleus accumbens determines the goal of action – which we want to perform (food, drink, sex, material assets, reputation ...) or which we want to avoid (pain, suffering ...) and chooses among alternative goals and behaviours. This structure represents the intersection of motivation and action. Ventral striatum and dopaminergic pathways in the midbrain are interconnected and have similar function.

Dopaminergic neurons encode two sets of information (i) current disproportion between expected and actual reward and (ii) long-term maintained signal, which correlates with uncertainty or reliability of the reward.

Dopaminergic system can be studied with the electrophysiological methods. It is characteristic that the dopaminergic neurons are active primarily in events connected with reward and new stimuli in the aversive stimuli the activity stops. In the reward related situations the activity is pulsatile, phasic and correlates with disproportion between the expected and actual reward (reward prediction error) and represent a type of learning.

Different aspects of reward (size, probability, delay) are processed and integrated separately. Electrophysiologic studies show firing of the dopaminergic neurones during the process of decision making. One study concluded [5] that the dopamine represents the value of the choice, the other study showed higher dopaminergic cell activity for the better option even in the absence of that choice [6].

Dorsolateral prefrontal cortex (DLPFC) receives input information on reward and reward prediction error from hierarchically lower regions (limbic system, ventral striatum, orbital and medial parts of prefrontal lobe) and integrates them with cognitively relevant data for the problem. Cognitive functions of the DLPFC include behaviour pattern inhibition, changing a set cognitive and motor behaviour and planning [7]. Final goal is to perform sensible, useful and adaptive behaviour. Studies on primates show high activity of DLPFC during reward expectation leading to proper and effective task performance. Current process is combined also with integration of past responses and response outcomes (reward, no reward) which is a basis for successful decision making process learning and behaviour.

Structures for reward oriented behaviour are connected to cortical and subcortical regions and modulate decision making processes and also other relevant processes, i.e. working memory. For the correct decision it is very important to integrate different possibilities and possible outcomes and to project, manipulate and evaluate them in the in working memory.

Rewarding system and decision making processes are strongly influenced through dopaminergic system by hormones and genetic characteristics (especially those in-/directly related to dopamine and enzymes involved in metabolism of dopamine). Rewarding system dysfunctions are described in several brain diseases, i.e. schizophrenia, Parkinson's disease, eating disorders, addiction etc.

ON FREE WILL

"If the moon, in the act of completing its eternal way around the earth, were gifted with self-consciousness, it would feel thoroughly convinced that it was travelling its way of its own accord on the strength of a resolution taken once and for all. So would a Being, endowed with higher insight and more perfect intelligence, watching man and his doings, smile about man's illusion that he was acting according to his own free will." (Albert Einstein: *On Free Will*).

The complex, cognitive-social processes of decision making are tightly related to the concept of free will. Do my actions represent my own free will, or they are just a reflection of necessity, which is independent of me? This dilemma escorts the mankind for thousands of years already – from the beginnings of philosophy and religion, until know, in modern society, when it is being related to the law as well as to the question of criminal responsibility. Opinions of philosophers, theologians, lawyers, about this issue differed enormously, from a pure determinism to a pure libertarianism. Kant [8] classified the decision making as one of the three metaphysical problems which are beyond the human intellect.

Libertarianism defines the free will as 'the power of subjects to be the ultimate creators (or originators) and sustainers of their own ends and purposes' [9]. The free choices, as defined by this concept, are absolutely causeless, without a reason: – we make a free decision when – without a previous cause – our decision produces the desired action. For example, a free decision would be the decision to go towards the refrigerator at a certain point of time. Indeterminacy and non–causality emerges in the moment one has decided to act. The nature and the source of decision are in that moment unknown, although it could represent the quantum indeterminacy of that event. However, very important questions remain unanswered – for example – who is actually the agent, who makes the decision of a certain action?

On the other hand, Hume thinks that a relational choice could not be un-associated with choice without a cause. Simple choices that we make are caused by previous mental phenomena – emotions, beliefs and so on. The decision to head towards the refrigerator could be caused by the feeling of hunger (for which one could actually be unaware of), but could not be completely without a cause. We should emphasize that some causes do not allow the opportunity of free choice. Many of them are related to more or less coercious choices, as Hume has put it nicely in one of his books:

"Where (actions) proceed not from some cause in the characters and disposition of the person, who perform'd them, they infix not themselves upon him, and can neither redound to his honor if good, nor infamy, if evil." [10].

Science has closed its doors before the concept of free will; it was even hostile towards it and has been defining the world as, speaking in general terms, determined system and system, whose determinants could be anticipated. However, the public opinion, at least intuitively, has been that free will does exist. At the end of the previous century, free will slowly became an object of investigation of the neuroscience and the answer to the problem given by neuroscientists was surprising.

The observations of patients with neurological diseases and the cognizance of the new scientific disciplines from the end of the 20th centaury has recognized the concept of free will and the related processes of decision making as valid scientific objective. The causative mechanisms of these processes are in the brain and are result of the brain activity. Clinical neurology, functional brain imaging and electrophysiology could be of great help in studying these phenomena. These methods determine the neurological conditions in healthy subjects as well in patients that have disturbed volition to execute movements and/or thoughts. The answer that the electrophysiological methods gave to the problem of free will was unexpected and surprising.

CLINICAL OBSERVATIONS IN THE NEUROLOGY AND PSYCHIATRY

We know that both, a low (drowsiness) and high level of excitement (anxiety, pain, intensive emotions) can reduce the will and the ability to make decisions. Neurologists and psychiatrists have been describing clinical pictures of patients in which the 'sick' will was present, the symptomatology being consisted of abulia, akinesia (poverty of movements), poverty of thoughts and reduced ability of decision making in general. The reduced or 'sick' will was described in schizophrenia, depression, autism, ADHD, dementia, Parkinsonism.

The concept of volition has been described by the neurologists mainly on the example of the motor actions or movements:

1. voluntary movements
   a) intentional (planed, initiated spontaneously and internally),
   b) initiated externally as a result of external stimulation;
2. semi-voluntary movements
   a) motivated by internal sensory stimulation (itching, akatisia),
   b) motivated with compulsion or undesired feeling (compulsive touching);
3. involuntary movements
   a) movement that can not be suppressed (reflexes, seizures, myoclonus),
   b) movements that could be suppressed (tics, chorea, tremor, dystonia, stereotypies);
4. automatic movements (walking, speech, alternating movement of the upper extremities while walking) are learned behavior patterns, which we execute without the conscious effort. They are probably encoded in the basal ganglia circuits (Jog et al.).

FUNCTIONAL BRAIN IMAGING

The brain imaging allows us to study the regional differences in the activity of the brain with high special resolution. The processes of decision making and execution of voluntary movements have been shown by using different techniques – with 2D extracranial measurements of the regional cortical cerebral blood flow (rCBF) [11] as well as with high resolution positron emission tomography (PET) [12]. The results of the functional imaging showed that the voluntary movements and voluntary decisions emerge in the prefrontal cortex and reflect the relation between the volition and dorsolateral prefrontal cortex, especially at the left side. Reduction of the prefrontal activities was shown to be present in many syndromes, for which 'weak will and weak decision making competency' is characteristic, as in schizophrenia, depression, dementia and Parkinson's disease, for example.

Parkinson's disease is a neurodegenerative hypokinetic movement disorder presenting with subcortical pathology. A high percentage of Parkinson's disease (PD) patients show cognitive impairments in addition to the cardinal motor symptoms [13]. These deficits primarily concern executive functions most probably linked to dysfunctions in prefrontal regions due to decreased dopaminergic transmission in fronto-striatal loops. Executive function is a higher order cognitive capacity that involves memory, perception and performance of complex tasks. Disorders of the executive functions are sign of lesions in the prefrontal cortex, involving the prefrontal-striatal-thalamic networks and the parietal association areas [14]. Damage in posterior dorsolateral prefrontal cortex and subcortical nuclei causes the dorsolateral syndrome with impaired decision making, working memory and planning. If lesion spares the basal forebrain (the ventromedial-orbitofrontal syndrome) memory can be preserved, but poor social decision making develops. Decision-making impairments in PD are most likely associated with dysfunctions in fronto-striatal loops. The mesolimbic and mesocortical circuits are particularly involved in reward-related behaviour in humans. Because these systems may be in some way altered in PD, it is likely that some psychiatric manifestations of PD, such as hedonistic homeostatic dysregulation and pathological gambling, as well as impulsive decision making, may be ascribed to their involvement [15]. Impaired decision making is implicated in addictive behaviours, and decision-making abilities can be influenced by dopaminergic medications.

Dementia in the setting of PD (PDD) may be among the most debilitating symptoms associated with disease progression. Estimates of cognitive decline and dementia in PD suggest that up to 14 % per year of patients over age 65 with PD will develop some cognitive impairment. Unfortunately, PDD is not well characterized and the relationship of PDD to Alzheimer disease remains unclear. Cognitive dysfunction is common already in patients in early PD, affecting attention, psychomotor function, episodic memory, executive function and category fluency.

A small pilot study in mild to moderate stage of Parkinson's disease dementia (16 patients, 71.2 ±4.28 yrs, with MMSE (Mini Mental State Evaluation) 23.1 ±0.57) on clinical correlates of brain SPECT (Single Photon Emission Computer Tomography) perfusion confirmed previously reported generalized cognitive impairment with predominant executive, visuospatial and attentional deficits [16]. Performance on specific cognitive measures was correlated with brain SPECT perfusion findings. A detailed neuropsychological evaluation, using a "cognitive process approach" focused also on measures of quality of executive planning, problem solving and decision making which positively correlated with perfusion in bilateral frontal cortex. Speed of cognitive processing and habitual response inhibition positively correlated with perfusion in frontoparietal regions – correlations were bilateral but stronger in the left hemisphere.

ELECTROPHYSIOLOGICAL STUDIES

Electrophysiological techniques can determinate the brain activity with very good time resolution (in comparison to functional brain imaging, which has good spatial resolution and bad time resolution). These methods are very useful when studying the time course of conscious decision making for a certain action and the execution of the action itself.

P300 AND DECISION MAKING

The relationship between the EEG recording (representing the neurophysiological brain activity), and its psychological meaning has been of interest since the first human recording of the electrical brain activity done by Berger in 1929. Since then, different strategies were employed in order to evaluate this relationship. One way to catch up with this problem is by analyzing the spontaneous EEG background activity (applying the fast Fourier transform i.e. spectral EEG analysis). The other way to do it is to analyze the brain electrical potentials that are specifically time-locked to events – the so called event related brain potentials – ERPs.

The events that are able to produce ERPs, can be defined as a segment of time at a given location that is conceived by an observer to have a beginning and end [17]. These events could be perceived by different sensory modalities – visual, auditory, somatosensory. No matter what kind of sensory stimulus is being applied in an experimental condition (in which one tries to elicit response), the evoked potentials have similar characteristics. Traditionally, two major classes of evoked responses were identified – exogenous (sensory) and endogenous ERPs. The characteristics of the first ERP type are largely depended by the physical properties of the stimulus itself. This type of ERPs are always elicited i.e. they are obligatory when a stimulus is perceived (e.g. brianstem potentials, elicited by sound). The endogenous potentials, in the other, hand are largely determined by the nature of the interaction between the person and the event. This person-event relationship is by nature very complex. Some of the endogenous potentials are even elicited in the absence of an external stimulus.

The most widely investigated endogenous potential is P300. This potential was described by Sutton and colleagues in the sixties as a late positive ERP wave, which occurs to task-relevant stimuli which carried carries significant information. Because the wave has a latency of about 300 ms and it is positive, it was called P300, although it was latter elaborated by other authors that this wave can be found anywhere between 250 ms and 900 ms. The P300 wave is produced by the typical oddball paradigm, in which, if we consider the auditory modality for example, two different sounds (different in frequency and/or duration) at different presenting rates are presented [18]. Until know, it has been associated with variety of cognitive activities – signal probability, attention, discrimination, uncertainty resolution, stimulus relevance, information delivery as well as with decision making [19].

Decision making is one of the most complex human behavioral processes. Decision-making processes have been object of research in philosophy, psychology and lately also in neuroscience, in which it is however still not enough tackled by the researchers. Many different approaches are used to investigate this process. In one P300 study, the participants were given a visual task with the second of the two rapidly presenting and relevant stimuli gave the opportunity to the subjects to make a decision [20]. Only the second stimulus produced a prominent P300. The authors speculated that the subject's activity as an information processor determined the P300 amplitude. The psychological correlate of the information processing was defined as decision making. In another study [21] young adults were required to detect auditory stimuli in split-second intervals. The early evoked potential components (between 100 ms and 180 ms) were reduced in amplitude by stimulus repetition, whereas the P300 component fully recovered in less than 1s. Their interpretation was that the P300, as a cognitive, endogenous evoked potential is recovered in parallel with the high-rate decision processes with which they are associated, which was also a base to postulate that the origin of early and late ERP is different.

In addition, some data show that factors that increase the duration of the decision process by affecting the speed of evidence accumulation (e.g. stimulus degradation, reduced stimulus intensity, increased display size in visual conjunction search) have generally been found to increase P300 latency and a reaction time by a similar amount. In the other hand, factors that affect post-decisional processing (e.g. complexity of the response) slow down reaction time while leaving P300 latency essentially unchanged [22].

Confidence of the decision making process can be defined as the ability of the participant to predict whether a given response will turn out to be correct [23]. Confidence in decision has been positively correlated to P300 amplitude, meaning that greater confidence of decision making produces higher P300 amplitude [24]. Furthermore, when the decision task is made easy, P300 starts varying as a function of the probability of occurrence of the second stimulus, in a way that, the lower the probability of the signal, the greater the P300 amplitude.

In summary, the P300 could be correlated to the decision making process itself. The P300 amplitude is enhanced when subjects are required to make a decision about stimuli. Also, it could be that greater P300 amplitude is correlated to greater confidence in the decision.

OTHER ELECTROPHYSIOLOGICAL STUDIES

Grey Walter [25] was studying patients, in whom electrodes were implanted in the motor cortex; he asked them to follow a sequence of slides, which they projected by pressing a false button – a button not actually connected to the system; slides were triggered by the electrical brain activity, recorded from the electrodes implanted in the motor cortex. The patients felt as if the projector anticipates their decisions, so to say, as if the projector switches the slides in the moment when they only had intention to switch the slide and right before reaching the decision to press the button.

In the same time, neurophysiologists demonstrated that 1 to 1.5 seconds before the execution of the voluntary movement, above the motor cortex a slow negative potential emerges (*Bereitschaftspotential* – Readiness Potential – RP) [26]. RP does not appear in the context of involuntary movements, and also does not appear before movements, triggered by external stimuli [27]. RP probably reflects the activity of the Supplementary Motor Area (SMA).

The voluntary action starts with determination of the purpose of the action, which lasts some time. When studying the planned voluntary movements, the researchers have found out that RP, preceding the actual flexion of the finger or wrist lasts few seconds. Grey Walter found that RP was detected in the RAF pilots before they have voluntary decided to drop off (simulated) bomb [28]. Libet investigated, when, in the temporal course of voluntary decision, RP appears, in comparison to the conscious intention for execution of an action. He expected that the electrophysiological study would confirm the concept of free will – the hypothesis that the free will causes the voluntary action.

He studied [29, 30] spontaneous and voluntary movements (flexion of the wrist, for example) and with the use of a very fast laser clock hand tried to determinate the time, when, in comparison to the beginning of RP and the voluntary action itself (as represented by electromyography (EMG)) the conscious intention and/or will for wrist flexion appears. The result, from neurophysiologic point of view, was somehow expected, whereas the result was bitterly unexpected from the point of view of the advocates of the concept of free will – the conscious intention for motor action appeared before the EMG signal and before the beginning of RP (Fig. 9). Libet tried to 'rescue' the concept of free will. The explanation of the result of his experiment, which was by the way reproduced several times afterwards, was that the voluntary movements were started unconsciously and that there was still time of about 100 – 200 ms before the actual execution of the movement to stop the movements. The free will and the voluntary decision in Libet's experiments relay more on the prevention of the actions than on the promotion of it. "We don't have free will, but we have free won't.", says Libet.

FUNCTIONAL ANATOMY OF THE VOLITION

As we will see, functional anatomy of the decision making and functional anatomy related to free will, volition, overlap. There are some movements, which are internally generated and in which people have feeling that the movements are result of free decision i.e. that we are the generators of actions we perform. Voluntary actions are related to the future and our goals directed towards the future are mainly generated in the prefrontal areas. These are for example – serial programming of the motor behavioural actions, language and cognition. In the same time, a process of suppression of those representations runs, which does not participate in the generation and execution of the voluntary actions. There are some studies, which define the prefrontal and the cingulated cortex as a part of the brain suppressing the irrelevant mental representations [31].

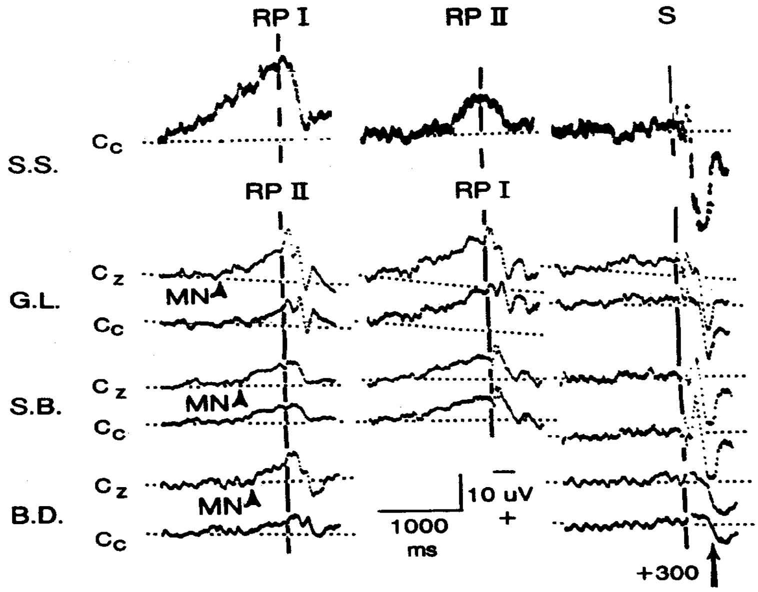

Figure 7. Libet's experiment – Readiness potential (RP).

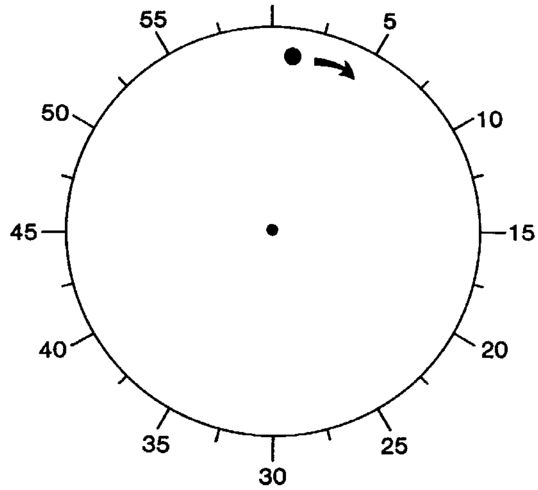

Figure 8. Libet's clock.

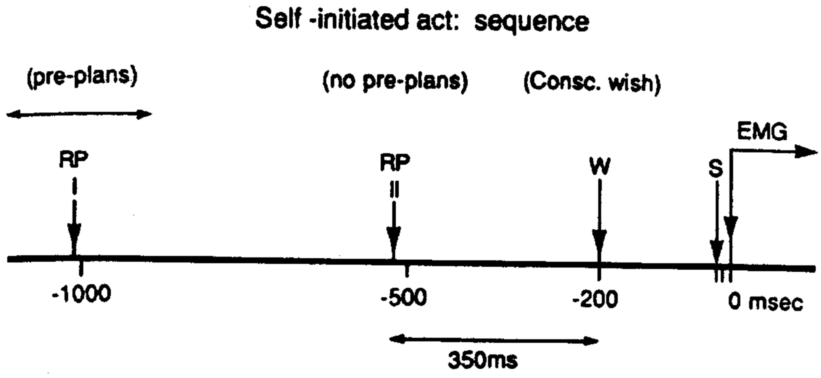

Figure 9. Time course of the readiness potential (RP), conscious intention (W) and movement execution (EMG) in the Libet's experiments.

Clinical examples of patients, electrophysiological studies and the new imaging studies confirm that free will (or at least the illusion of it), could be to a certain level prescribed to different brain regions. Different brain regions participate in the execution of consciously selected voluntary movements or thoughts. Most of them lie in the prefrontal cortex as well in the connection of the prefrontal cortex with the subcortical nuclei – already mentioned cortical-subcortical-frontal loops. The loops are half-opened. They connect wide areas of the cerebral cortex with the basal ganglia, thalamus and the frontal cortex [1]. There are at least five different loops. For the concept of free will two of them are of greater importance: (i) mesial loop, which ends in the anterior cingulate gyrus in the orbitofrontal region and in the in SMA and (ii) lateral loop, which ends in the dorsolateral prefrontal cortex.

The anterior cingulate gyrus (Fig. 10) is a place where motor, emotional, homeostatic and cognitive processes get in touch to each other and than mix in order to produce proper choices. SMA plays an important role in sequencing and programming of the course of motor actions, which are necessary for execution of a certain motor plan.

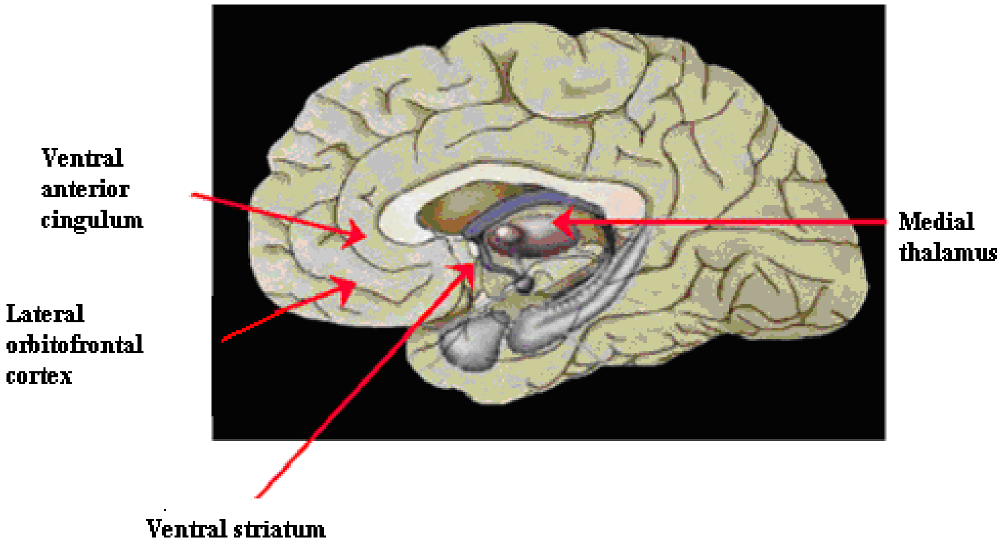

Figure 10. Cingulate gyrus.

As we have already mentioned, the orbitofrontal region participates during the modeling of actions with regard to reward, punishment or the social context, in the same time suppressing the exaggerated activity of the deep structures (basal ganglia, limbic system). The dorsolateral prefrontal cortex forms plans and sets goals and also participates in the process of choosing of the response, especially if the context is new, or if the action is generated internally. This part of the brain has an important role in the working memory.

So, the prefrontal regions are essential for decision making processes and the feeling of free will. Consequently, they are related to the feeling of "I", which in the western culture represents a complex net of goals, interests, fears, which affects our decisions at the conscious and unconscious level – in the former case, the feelings could be regarded to be the cause of our actions and in the later case, we would react, without knowing the reason for the reaction.

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ODLUČIVANJE I MOZAK: POGLED NEUROLOGIJE

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SAŽETAK

Članak oslikava činjenicu kako koncepti poput odlučivanja i slobodne volje ulaze u područje kognitivnih znanosti pri kraju XX. stoljeća. U članku je dan pregled struktura mozga uključenih u odlučivanje i koncept slobodne volje. Prezentiranjem rezultata kliničkih promatranja i novih metoda (funkcionalnog neuro-oslikavanja, elektrofiziologije) postulira novi mehanizam provođenja tih koncepta. Dan je prikaz neuroanatomije s posebnim razmatranjem dijelova mozga značajnih za navedene teme, jer je donošenje odluka ovisna o duboko subkortikalnim kao i kortikalnim strukturama. Dopamin je središnje uloge za ponašanje povezano s nagradom i hedonizam. Također, navedena je lista struktura mozga povezanih s dopaminom. Članak posebno naglašava studije SPECT za ispitanike s Parkinsonovom bolešću (neuro-oslikavanje), kao i studije povezane s potencijalom spremnosti i endogenim potencijalom P300 (elektrofiziologija). Na kraju, razmatramo želje, čija se funkcionalna anatomija preklapa s funkcionalnom anatomijom slobodne volje i procesa odlučivanja.

KLJUČNE RIJEČI

Kognitivna neuroznanost, mozak, odlučivanje, slobodna volja, elektrofiziologija, funkcionalno oslikavanje, dopamin