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RESEARCH ARTICLE

Thermodynamic view on decision-making process: emotions as a potential power vector of realization of the choice

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Abstract This research is devoted to possible mechanisms of decision-making in frames of thermodynamic principles. It is also shown that the decision-making system in reply to emotion includes vector component which seems to be often a necessary condition to transfer system from one state to another. The phases of decision-making system can be described as supposed to be nonequilibrium and irreversible to which thermodynamics laws are applied. The mathematical model of a decision choice, proceeding from principles of the nonlinear dynamics considering instability of movement and bifurcation is offered. The thermodynamic component of decision-making process on the basis of vector transfer of energy induced by emotion at the given time is surveyed. It is proposed a three-modular model of decision making based on principles of thermodynamics. Here it is suggested that at entropy impact due to effect of emotion, on the closed system—the human brain,—initially arises chaos, then after fluctuations of possible alternatives which were going on—reactions of brain zones in reply to external influence, an order is forming and there is choice of alternatives, according to primary entrance conditions and a state of the closed system. Entropy calculation of a choice expectation of negative and positive emotion shows judgment possibility of existence of "the law of emotion conservation" in accordance with several experimental data.

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Introduction

In recent scientific paradigm the myth about rational human nature and human thinking was triumphed. After World War II the core of new consolidation became so-called "a neoclassical synthesis", turned into a mainstream. The Keynesian model was applied to misbalance cases in macroeconomic, and in the analysis of situations of the general balance and in microeconomics the neoclassical theory was used, however gradually economists began to refuse traditional model of a rational choice. In the 1950th there was a concept of "behavioral finance"(Olsen 2001). Since the end of the 1960th articles of P. Slovic, D. Kahneman and A. Tversky were published and, finally, in the 1970–1980th there was created so-called "a theory of prospects". Thus in models of economic psychology tested hypotheses of parameters of expected utility and intertemporary consumption in the conditions of uncertainty already began to be offered. The last 20–30 years there was a revolution of scientific thinking, the bright researches which have convincingly proved irrationality in a choice of the decision (Kahneman and Tversky 1979) are carried out. Decision-making is, probably, one of main types of activity, characteristic for human beings. That is why attempt to understand, explain and predict behavior of the individual making a choice became the main task of behavioral and social sciences (Kahneman and Tversky 1979).

In the modern world the economic science experiences paradoxical difficulties. Despite dynamic and technological

development of the market, there is the problem and inconsistent situations bound to social and economic, political, culturological and religious dogmas, level of political education and development of economic institutions in different –economic-socio-political societies, especially being shown in the conditions of uncertainty. Not news that today's reality is characterized by the state of instability, prompt changes in political arena, and, as a result, lack of economic stability as at the international, state level, at level of separate segments of the population, and at level of separately taken people. World economic crisis, the cascade of revolutions and changes of ruling regimens in the states of North Africa, natural cataclysms, mass demonstrations in the countries of Europe, the Middle East and the USA referred against increasing stratification of society and social injustice;—all these are signs of growing discontent with the existing world system. Ascending and implication of a social pressure—a sign of instability and emotional strain of persons, social groups, people, reduce of definiteness as economic medium at the level of the states, as well as at the level of an individual. Laws and theories of development of subjects of vital activity of the person, including the world community, continents, the countries, regions, subjects of managing and a household are based generally on synthesis of the previous historically saved up experience. Today instruments of forecasting of human systems, especially during the periods of their bifurcation changes (the periods of strongly nonequilibrium states or states of uncertainty) are developed insufficiently. Globally evolutionary developments of social and economic systems are directly bound to behavior of the "elementary particle" which functions in these systems are carried out by an individual. At all differences the general tendency of movement of an economic science consists in development of more realistic initial axiomatic, and, first of all in idea of structure of mentality of the person and his behavior. Classical and neoclassical economic theories and their derivatives are subject to criticism as they proceed from an axiom about the person rationally maximizing individual welfare (understood as the monetary income or wealth care). The neoclassical theory proceeds from an equilibrium or balance state of market capitalist system. Market balance is first of all a supply and demand equilibrium state in two congruent markets—goods and services, on the one hand, and production factors—on the other hand. It should be noted that fact that in the course of any economic operation due to both objective, and the subjective reasons we can observe regular and spontaneous shifts from an equilibrium state in this or that way. Often such shifts happen as a result of previously made decision. Referring to the works executed by Akerlof (2001), Sen (1973), Manski and McFadden (1981), Stiglitz and Walsh (2002), Smith (2009), it is possible to consider as proved that economics not that sphere where subjects of economic activity can make decisions, relying only on rational thinking. Cartesian (exclusively logical) thinking seems can serve only in quality of the auxiliary correcting mechanism within the general psycho-rational system of development of economic judgments.

Psychology as the science, on the one hand hardly exists more than 150 years. On the other hand, the attempts to explain mental laws exist exactly as much as the history of human thought. The psychology in the development changed the object of research with all the heart during the Antique era, through reason and perception researches during New time, having concentrated on perception and mentality functions as adaptor mechanism in the nineteenth century, to research of consciousness and cognitive processes in the twentieth century, and in parallel—to the analysis and studying of unconscious phenomenon (Nurkova and Beresanskaya 2010). To the person far from scientific research of psychology, it can seem strange that till eightieth of the twentieth century, research of human mentality practically didn't concern the implication most inherent to the person—emotions. It is possible to explain this fact by extreme complexity of measurement, differentiation and a vector of emotional processes.

D. Kahneman and A. Tversky's works (Kahneman 2003; Kahneman et al. 1991; Kahneman and Tversky 1979, 1984; Tversky and Kahneman 1974, 1981), experimentally have illustrated that decisions which are accepted by the person aren't rational and confirmed thoughts and intuitive feeling of a great number of researchers. However, if the person who possesses intellectual potential, a huge arsenal of information sources and means of information processing, makes irrational decisions, then what influences on the process and results of decision-making?

Kahneman's scientific merit is not only in that he partially proved the hypothesis about dominance of irrational decisions (fast, spontaneous, not passed through rational verification) over rational calculations in behavior, but he also explained the series of typical errors of irrational decisions. Intuitive choices are decisions based not on the rational analysis of a situation, but decisions which the person accepts relying on emotions. Emotional, intuitive decision-making is described by the set of idiomatic expressions in different languages: "internal feeling", "that is my way" , etc. Dominance of emotions is explained by the fact that affective decisions are reactions to the aspects more available for perception. There are also distortions inherent in perception: (a) similar objects are perceived easier, than differences, (b) changes of objects are more appreciable than their absolute values, (c) average values are easier, than sums of values and (d) it is given larger specific gravity for more available values, than for ones less available ("Binding Effect").

Group of researchers (Rangel et al. 2008) structures decision-making process on some stages, relying on neurobiological data. At the first stage there is a task formulation, idea of the purpose and context of a decision are formed (1). There are integrating of information on internal body state and environmental factors. At the following stage the value of choice of one or another behavioral alternative is defined (2). At the third stage the alternative solutions are compared, and there is a choice of the best one is chosen (3). After exercise of the chosen action there is a processing of its results and an assessment of effectiveness (4). At the last stage there is learning, i.e., updating of information which was stored in memory so that all subsequent actions would carried out with the greatest effectiveness.

Thus in human brain there is a process of comparison of desirable result and real situation, a choice of the action required for achievement of the necessary purpose. This process doesn't reach consciousness: comparison is so quickly made. We "feel" that our decision is reasonable when positive emotion supports the best choice.

Neuroeconomics uses knowledge about brain mechanisms to inform economic theory. The key insight for economics is that the brain is composed of multiple systems which interact. Brain evidence complicates standard assumptions about basic preference, to include homeostasis and other kinds of state-dependence, and shows emotional activation in ambiguous choice and strategic interaction (Camerer et al. 2004). Economists generally emphasize rationality; psychologists emphasize cognitive limits and sensitivity of choices to contexts; anthropologists emphasize acculturation; and sociologists emphasize norms and social constraint. It is possible that a biological basis for behavior in neuroscience, perhaps combined with some other natural sciences standpoints, could provide some unification across the social and natural sciences.

Non-linear dynamic model of decision-making

At each present moment in our brain there is an analysis of impressions and emotions, comparison of observations with affective and evolutionary memory, the formed images and behavior models that, eventually, lead to some prior conclusion. Evolution of such systems can be determined by behavior of individuals in interaction with conditions imposed by environment. Distinction between desirable and true behavior probably acts as the external condition of new type defining contours of dynamics along with environment.

How we make decisions in the situation of just uncertainty when we are unable to estimate and predict its development on the basis of the previous experience? Whether past experience for a future prediction is sufficient or high degree of unpredictability of the future makes an essence of human acts? Apparently, the intuitive feeling is focused on the second alternative. Whether mathematical approach allows showing this intuitive feeling—for what we will try to estimate the advantage which is bound to this choice. It seems that it is impossible to predict human acts; however we will try to describe attractiveness (or probability of decision-making in the situation of indeterminacy) with help of mathematical apparatus of non-linear dynamics. Excluding casual chance, the desirability of acceptance of exact i-decision from K alternatives at unit of time is proportional to the relative appeal of i-option. As there is a decision-making of rather this option, generally the advantage changes, so it will be reflected in a picture of the preferable options in the form of increase or decrease of attractiveness of the corresponding choices. The similar dilemma called by I. Prigogine as "loop of a feed-back" (Prigogine and Stengers 1997; Nicolis and Prigogine 1989), is shown on Fig. 1 for two alternatives of a choice: α and β.

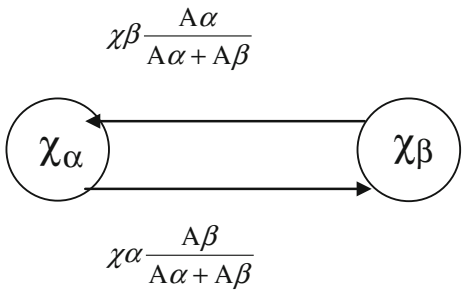

Fig. 1 "The loop of a feed-back" characterizing realization of a choice under condition of two at the same time existing possibilities α and β, which degree of attractiveness is characterized by numbers Aα and Aβ. Number of emotions inducing a choice α and β, are designated χα and χβ respectively

Here Aα represents attractiveness of a choice α, and χα—number of emotions inducing a choice α to the current time. A relative number of the emotions assuming change of a decision making on a choice β, is proportional to the number of those emotions in favor of which another choice of type α is made, and to the relative attractiveness of a choice β, defined as Aβ/(Aα + Aβ). The same way the number of emotions assuming change of a choice β on a choice α, in proportion χβ increased by the relative attractiveness α, equal to Aα/(Aα + Aβ). It leads to the set of equations for χα of balancing type:

$$\frac{d\chi\alpha}{dt} = \alpha\chi\alpha\left(\frac{\chi\beta A\alpha}{A\alpha + A\beta} - \frac{\chi\alpha A\beta}{A\alpha + A\beta}\right) \quad (1)$$

or, taking into account that χβ = N – χα, where N—the total spectrum of emotions,

$$\frac{d\chi\alpha}{dt} = \alpha\chi\alpha\left(\frac{\mathrm{NA}\alpha}{\mathrm{A}\alpha + \mathrm{A}\beta} - \chi\alpha\right) \quad (2)$$

The similar equation we receive for χβ:

$$\frac{d\chi\beta}{dt} = \beta\chi\beta\left(\frac{\mathrm{NA}\beta}{\mathrm{A}\alpha + \mathrm{A}\beta} - \chi\beta\right) \quad (3)$$

Comparison of these equations allows drawing a conclusion that the existence of various alternatives influences bearing capacity of a system (human brain) which becomes the function of instantaneous condition of the system at the expense of dependence of attractiveness on variables χ.

The stipulated ideas are easy to generalize on a case of the arbitrary number of the set C of choices K taking into account more substantial situation when attractiveness of i-option depends on j emotion which induces a choice. We receive, thus the system of equations:

$$\frac{d\chi i}{dt} = C\chi i\left(1 - \frac{\chi i}{\sum_{i=1}^{K} \frac{\mathrm{Nj}\mathrm{A}ij}{\sum_{r} \mathrm{A}ij}}\right) \quad (\mathrm{i} = 1, \ldots, K) \quad (4)$$

In this case it is supposed that the ensemble of emotions is non-uniform, and breaks up into some various categories Nj regardless of valence, each of which induces the idea of relative attractiveness of the alternative of decision. The behavior described by the last equation of dynamic system, dominantly depends on the nature of dependence of attractiveness of Aij and Nj on variables χi characterizing the instantaneous condition of emotion. This dependence also is defined by the parameters of environment and by the possibilities of influence of emotion or their associations on a human brain at each fixed period of time. Attractiveness of a decision making is a subjective but at the same time an adequate answer to emotion, regardless of its valance. Besides, there is a discord in decision-making process—the response to any charge of emotion. There are two scenarios possible here. In the first and most obvious case positive emotion leads to the useful decision and negative emotion—to inefficient. In the second scenario a negative emotion can act as the catalyst of advantageous decision, and positive emotion, on the contrary, can induce an ineffective choice.

Thermodynamic approach to decision-making process

At the beginning of this section it is expedient to mention a series of academically and practically interesting researches of an assessment of energy efficiency in brain functioning, mechanisms of governing the evolution of cortical networks, innovative theories of informational energy coding (Levy 1996; Raichle and Gusnard 2002; Simon et al. 2003; Wang and Zhang 2006, 2007; Wang et al. 2008, 2009; Feldman 2012; Cohen et al. 2007; Levy and Baxter 2002; Pakhomov and Sudjin 2012).

Earlier researchers Gross and Thompson (2007) have carried out the analysis and evaluation of core features of emotion. They observed the situation—attention—appraisal—response sequence specified by the modal model of emotion. They indicate that the emotional responses generated by appraisals are thought to involve changes in experimental, behavioral and neurobiological response systems. There are several other models emphasizing the complex of choice: mechanistic models of decision making, behavioral models based on information theoretic bounds on predictive performance (Corrado and Doya 2007; O'Doherty et al. 2007). Models include explicit decision variables that can be calculated on every trial; these quantities can then be used as proxies for the state of the subject's true internal decision variables.

We will consider here the case of influence of emotion on behavior of an individual given to theoretical system, in which environmental factors (threat or usefulness levels in the context of future action/decision) are ignored. Emotion will be considered as the function of vector transfer of energy in the loop system of movement and of analysis of possible alternatives of decision-making. From the point of view of the sequence of events our model can be presented as follows: impact of emotion (1) → analysis of alternatives (2) → decision-making and adaptation to the choice (3).

From the standpoint of decision-making evolution process on the basis of vector transfer of energy, the model will schematically look as follows (Fig. 2):

At the first stage (Fig. 2a) emotion which is comparable with energy of external system, influences closed system—human brain zones where fluctuations and the analysis of possible alternatives, taking into account the influence of accumulated emotional and cognitive experience, in reply to the emotion vector are going on. Though, the most probable it's seemed to be that the rational component in this situation is a noise. At the second stage the decision which will operate further behavior of an individual and will be transferred into environment is formed. Further implements adaptation to and/or at the same time, there is to be probable further analysis of already made decision at present which will evolutionary sedimentated in reply to an affect memory in the zone of a rational choice—a dorsolateral frontal cerebral cortex (DLFCC) (Miller and Cohen 2001; Rosenbloom et al. 2012). Sometimes even at this stage made decision can be either emotionally or rationally changed (e.g., it was decided to buy a pullover which was pleasant and suitable, but on the way to the cash desk it was found another pullover which is not at all conceding to the chosen one). Than the process is coming back to one of the options of three modular model.

Extrapolating data (Rangel et al. 2008) on the model shown in Fig. 2a, we receive the following integrated

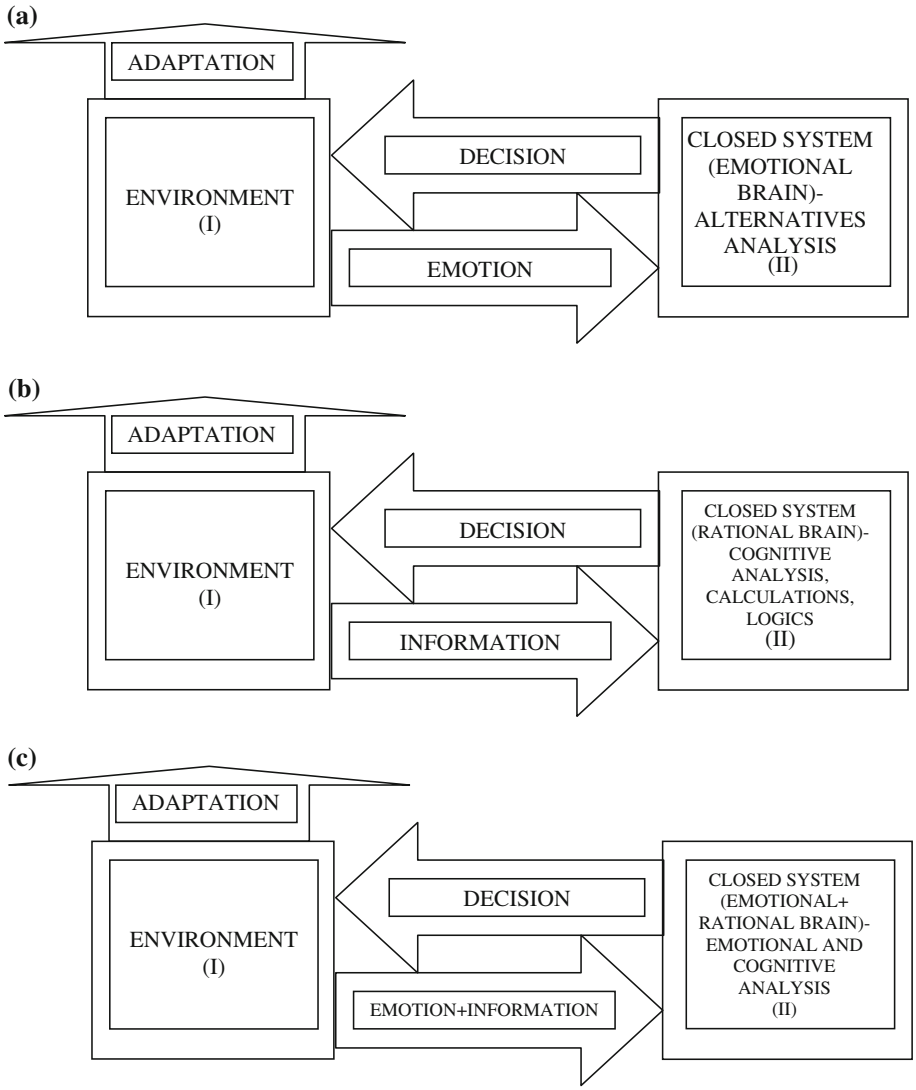

Fig. 2 Three-modular model of decision-making mechanisms based on thermodynamic principles. **a** Emotional decision, **b** cognitive decision, **c** emotionally and cognitively driven decision

processes. In the environment (I) initially there is an emotional reaction or the cascade of emotional splashes, in reply to the occurred event. Emotion influences the corresponding sites of a brain and the closed system (II) in which value of a choice of this or that behavioral defined mechanism is involved in process, the alternate options are compared, including sedimented both emotional and cognitive experience, and there is a choice of expected to be the best decision. Then process is transferred to environment (I) in which there is an adaptation to the decision and tutoring of the individual, i.e., updating of information which was stored in memory so that all subsequent actions were carried out with the greatest possible effectiveness.

The thermodynamic studies conducted by Nobel laureate Prigogine I. (Prigogine and Defay 1954; Kondepudi and Prigogine 1998) show that any of processes occurring in the nature are irreversible. All processes are irreversible though it is possible to think up some actual processes as wished to be close to the reversible. Thus, reversible processes should be considered as an idealized limiting case (e.g., ideal gas) to which actual processes can approach under the corresponding conditions. Concerning reversible processes it is possible to discuss only as about hypothetical idealized processes. In other words, it is impossible to return system to an initial state so that from happened event did not remain any trace. For instance, in case of the pen which has fallen from a table, there were following processes: its potential energy transferred at first into kinetic energy, and then into the heat dissipating in environment. The pen which has fallen from a table, of course, can be lifted and put on the same place, however in the surrounded

world there are indelible traces: the potential energy of the pen dissipated in the form of heat, and in our body at a rising of the pen there were various biochemical and biophysical processes.

We suppose it is apparent that proposed here model should be considered as an irreversible process as we can't say even with small probability that the system from the state II will return to the state I, without having undergone changes. Additionally, it would be desirable to characterize system (II) considered in this research from the standpoint of thermodynamics as loop (closed) system because the system which cannot exchange matter with environment is called closed;—the only exchange of energy is possible (Prigogine and Defay 1954; Kondepudi and Prigogine 1998). Let's consider in our case a thermodynamic indicator "entropy",—which is the index of evolution, or according to Eddington "time arrow" (Eddington 1928). Thanks to entropy, the system in which there is initially a chaos, aspires to an equilibrium state and to the answer energetically adequate to external influence. The unit S which depends only on initial and terminating states and doesn't depend on transition from one state into another, called an entropy (from Greek—transformation), allows to describe an irreversible process as follows:

$$dS = dSI + dSII;$$

or proceeding from the record of the second law of thermodinamics offered by Klauzius in shape:

$$dS = \frac{\delta Q}{T} + \frac{\delta Q'}{T};$$

for all irreversible changes in closed system

$$dS \succ \frac{\delta Q}{T};$$

entropy increment (characterizing entropy exchange of closed system with environment), in frames of our model it is possible to impress as follows:

$$dS = \frac{\delta Q}{T} + \delta SII$$

here *dSI* is the change of system's entropy, caused by exchange of energy with environment, *dSII* is the change of entropy caused by irreversible processes in system, δQ—calorie of environment, δQ′—noncompensated calorie, always positive for closed systems, T—absolute temperature.

Thus, the entropy of system can be changed owing to only two reasons—either as result of transfer (transport) of entropy from environment or into environment through system borders, or as a result of entropy emergence in very system. For the closed system the stream of entropy *dS* can be both positive and negative and the entropy of system can both increase and decrease. Surely positive has to be entropy emergence *dSII* caused by changes in system, but not entropy increment *dS*. In case the system is in a condition of a thermodynamic equilibrium, the velocity of increase of entropy is equal to zero.

In our case emotion as the energy vector influences mentality of person, the corresponding sites of a brain being closed system. When this system starts analyzing alternatives in reply to emotion, it generally leaves equilibrium state due to fluctuations of decision searching and brings system into chaos, generating irreversible processes in closed system. After the analysis of possible alternatives spectrum is carried out and the decision is made, the entropy by an exchange with environment stabilizes closed system, returning it out of chaos, brings the zones of a brain activated by emotion into equilibrium state. As according to Kondepudi and Prigogine (1998) the entropy grows in irreversible processes, and in the reversible—does not change, we believe that significant increase of entropy, instead of its invariance on a phase of the alternatives choice in reply to emotion impulse, leads system to chaos and then balances it.

In the shown mechanism the possible analogy is looked through data of some biochemical investigations. In particular, the considerable heterogeneities are observed at cellular level. The potassium ion concentration in neurones is much higher, than in the extracellular environment whereas for an ion concentration of sodium the revertive situation is observed. These differences which mean the strong disequilibrium underlie processes like innervations. Noted misbalance is supported by fissile transport of chemical components, electric and bioenergetics' reactions such as glycolysis and respiration (Volkenstein 1988).

In case of domination of a cognitive component over emotional (Fig. 2b) the closed system reacts to the situation which has arisen in environment by means of the rational analysis, calculations, logics, comparing incoming information with the evolutionary accumulated experience fixed in memory. In this case emotion probably is a noise, a kind of background. At the following stage the created decision is transferred into environment, than also there is an adaptation to the decision and training of the individual. The cognitive analysis requiring calculations, obviously, longer while, than emotional reaction results. At the same time, in the closed system there is no fluctuations lead to chaos, bifurcation conditions are not formed and dissipative structures are not appeared. In spite of the fact that in connection with energy assumption, production of entropy *dSII* in the closed system will be still carried out, its increment *dS* will be much lower, than in case of emotionally made decision. As the decision is rigid it can hardly be reconsidered at the stage of adaptation to the made decision.

Let's consider the opportunity (Fig. 2c) of decision-making in terms of competition of emotional impact and

rational approach. Process of decision-making is represented generally to be similar to the way of emotional decision. The main difference is that in case of the emotional decision, the cognitive component was more noise, than in this case. Here the rational brain enters fight for leadership with emotion. Anyway ideal in this mechanism might be the situation when in a counterbalance to fight; emotion harmoniously supports the cognitive decision. From the thermodynamic point of view, as a whole, process will be proceed as the sum of two earlier described processes (Fig. 2a, b), and entropy increment can be expressed by the following equation:

$$dS = dSI + dSII = dSI + d(Se + Sr) = \frac{\delta Q}{T} + \frac{\delta Qe' + \delta Qr'}{T};\ \text{here}$$

Se—entropy produced in the closed system due to emotion, *Sr*—entropy produced in closed system due to cognitive process, $\delta Qe'$—noncompensated calorie of emotional brain, $\delta Qr'$—noncompensated calorie of rational brain.

Several investigations suggest that value might be encoded by neurons in numerous brain regions, including dorsolateral prefrontal cortex (Lee and Wang 2008), premotor cortex (Roesch and Olson 2003), frontal eye-fields (Roesch and Olson 2003), supplementary eye-fields (Stuphorn et al. 2000; Roesch and Olson 2003), superior colliculus (Ikeda and Hikosaka 2003), basal ganglia (Kawagoe et al. 1998; Doya 2008), amygdale (Paton et al. 2006), and centromedian nucleus of the thalamus (Minamimoto et al. 2005). Platt and Padoa-Schioppa (2008) propose that value signals expressed by different neuronal populations contribute to different mental processes. In sensory areas, value signals may contribute to perceptual attention (a process of choice between different sensory stimuli); in frontal areas, value signals may contribute to economic choice (a choice between different goods); in motor areas, value signals may contribute to action selection (a choice between different motor acts). Miller and Cohen (2001) describe that prefrontal cortex playing an important role in cognitive control, in the ability to orchestrate thought and action in accordance with internal goals. They believe that cognitive control stems from the active maintenance of patterns of activity in the prefrontal cortex that represent goals and the means to achieve them. They provide bias signals to other brain structures whose net effect is to guide the flow of activity along neural pathways that establish the proper mapping between inputs, internal states, and outputs needed to perform a given task.

In the closed system initially there is a chaos, fluctuations of possible alternatives—responses to external influence of emotion which then are ordered or/and rational calculations in response of income information, and finally there is a choice, according to initially given entrance conditions and to the state of the closed system. The choice is carried out either spontaneously or selectively owing to sedimentation of the accumulated evolutionary experience of the individual and due to effect of emotion or cognitive approach. Other factors in our case are insignificant, in connection with the initial stipulation on ideality of system. In case of the selection choice we can assume momentary surge in entropy which as a result will balance an equilibrium state of the closed system in the form of the decision. The entropy following from the closed system, always higher than the entropy entering into the system; the difference arises because of entropy produced by irreversible processes inside the system. Our system which exchanges entropy with environment, possibly, in case of emotion or combination of emotion and mind undergoes very strong spontaneous transformations, transferring into a self-organizing mode. Order achievement through fluctuations is possible only in essentially non-linear systems (from trigger threshold processes of transfer of a nervous impulse up to evolution, irreversible development of biological systems). Such organized states are created by irreversible processes making entropy. Correspondingly, it seems that irreversible processes are that motive power which creates an order.

For the most objective and overall estimate of the crisis situations occurring in the modern world, it is required the balanced comprehensive approach involving economic, socio-political, demographic components, a level of development of culture, education, health care, communications, infrastructure, religious aspects, scientific and technical potential, the safety doctrine, the foreign policy and external economic relations, moral foundations, the ideological doctrine, historical way and other, not less significant components of a system of each exact state. However, we will try to describe some scenarios of events happening in the world today in frames of thermodynamics.

Demonstrations, excitements, protests of people which aren't agree with the accepted political order. The motive power is an anger, indignation and discontent. Let's consider Egypt events in 2011. Masses of people went out; demonstrations were accompanied by disorders, attempts of their suppression—establishing order in system, approximating system to an equilibrium state. As a result of mass expression of discontent, confrontation between authorities and people, the following was happened: change of a political regime, displacement and the subsequent detention of the head of the government, gradual "order establishing"—irreversible changes which occurred in the system. As an example when the level of emotional pressure didn't overcome threshold value, and didn't lead to government change,—mass demonstrations in Israel in the summer of 2011. Hundred thousands people three times were going out to express the disagreement with a course of the present government, increasing level of social tension and society stratification.

Having witnessed events, it would be desirable to note that, despite general discontent, participants of a protest were in good mood, there were no appeals to violence, manifestations of aggression, anger and rage. Law enforcement bodies were keeping complete respect for participants of street processions. Internal strength, anger and other negative emotions suppressed for a long time in Egypt led to the considerable emission of energy in system, and, finally—to the change of the government and political orientation of the state (entropy increase → chaos → irreversible change of system → return to the order). In Israel neighboring Egypt the level of emotional pressure in the summer of the same 2011 didn't exceed threshold value, with entropy increase the system didn't pass a chaos threshold, and the system returned to the initial state.

Comparing situations, we can see that, reaching a bifurcation point, emotional factors focused system onto a choice of different paths. At the enterprises and in society, as a whole, analog of such fields provoking surge of emotional influences can be social and psychological atmosphere, cultural and business traditions, moral foundations, religious dogmas and others. Similar ways of influence are in the markets, but there is a general problem that in the complex system with the strong non-linear internal and external relations it is impossible to predict in advance reaction of system to emotional influence. As it is impossible to make unequivocally right choice "for system", it is necessary to use as much as possible its ability to self-organizing and a self-contained choice of the way of development in frames of complex set of external (automatic) and own conscious administrative active influences. At the same time, it means that the impact on system should be based on both systemic complex emotional and rational basis.

From the microscopic point of view, the order in polypartial system is represented in the form of various collective conditions and their superpositions. Particles probably in such conditions behave not independently, but consensually therefore the organism functions as a unit. In formation of collective conditions the deep natural meaning is concluded. Authors believe that the basis of meaning of the life of living organisms consists in actual idea of survival to realize reproductive function as an evolutionary mission. It is known that living systems are principally nonequilibrium (situated in exited energy condition). The ground (nonexcited) state for them is a death. Proceeding from Heisenberg indeterminacy principle as less excitation energy as longer the system lives. Low-energy excited states of system just also are satisfied by collective conditions. Usually a range of such conditions is discrete (or quasidiscrete) therefore transitions between conditions are carried out by jumps, with release or energy consumption. Stable quasidiscrete states are peculiar to all living and social bodies, including enterprises and households. Therefore sometimes it is very difficult to change an enterprise condition continuously and gradually—small revolution or crisis for this purpose is required. In general development of systems leads to their continuous complication, however, excessively complex order in the critical case bears a strong resemblance to chaos, of only other scale—the system becomes again uncontrollable and disorderly.

Entropy approach to the classification of emotions

Recently psychologists more often address to the questions raised by thermodynamics and characteristic index of the second law—entropy (Izard 1977, Hirsh et al. 2012). From described above states when this index is minimal can be entropy limits for the person, and the person isn't capable to adapt to the changing world, and, on the contrary, at very high entropy value, the state of mentality of the person reaches borderline states. From the standpoint of directional transfer of energy, emotion might be structure on that which promotes increase of a psychological entropy, and emotion which, on the contrary, facilitate rational behavior. Being based on vector entropy energy nature of emotions, and also in view of possibility of manifestation of a discord in the process of decision-making—response to this or that charge of emotion, it is represented expedient to group emotions in three following categories: conditionally positive emotions (pleasure, admiration, delight), conditionally neutral emotions (interest, surprise) and conditionally negative emotions (suffering, anger, disgust, contempt, fear, shame, guilt).

Correlation of thermodynamic and informational entropy in the process of alternative choice

Ludwig Boltzmann offered the following ratio between microscopic conditions and entropy to reconcile a reversibility of mechanics with nonreversibility of thermodynamics: $S = k \ln W$, where W—number microstates corresponding to that macrostate, which entropy is equal to S, k—a Boltzmann constant. From the second law of thermodynamics, using Boltzmann's stochastic approach it is received the following equation:

$$dS = dSI + dSII = k \ln W = -\sum (Pd) \ln P(d);$$

where $P(d)$ is expectation of that casually chosen alternative will lead to the decision d.

The concept of thermodynamic entropy is bound to determination of Shannon entropy (Shannon and Weaver

1949) which expresses the uncertainty of realization of a random variable. Thus, an entropy is a difference between information containing in the message, and that part of information, which is precisely known (or it is well predictable) in the message (Volkenstein 1986). In our case a statistical entropy of Shannon can characterize a difference in information received by human brain through emotion and that information containing in emotion, which is familiar (or well predictable) thanks to affect memory of the person. The same process is accompanied by dopamine reinforcement of correct decision from the affect memory standpoint. There is the exaltation of dopamine neurons causing positive emotions and probably shifting system towards irreversible changes (Damasio et al. 2000; Schultz 2007).

In case all probabilities of alternatives are identical, in system there is a chaos and systems indeterminacy (disequilibrium) is maximal. In strongly nonequilibrium situations dissipation structures—existential formations (such as semi-decisions which further, will be probably changed) can be created. The dissipation shows that unlike dynamic reactions thermodynamic reactions are temporally and operated not finally, and probably, events will develop further according to certain other scenario. Sometimes they undergo spontaneous changes. If one of probabilities of alternatives of the decision is equal to one ($P = 1$),—other probabilities of alternatives in this case will be equal to zero, so indeterminacy is absent and there is no chaos in system. Indeterminacy in this case is equal to zero. We receive the conclusion that entropy S is located in the following range: $0 \leq S \leq 1$. As a whole, in our system at first there are spontaneous fluctuations of choice alternatives then selection of alternatives comes into force and irreversible evolution of system of behavior in reply to the accepted decision begins.

About "an emotion conservation law"

In researchers (Heller 1993; Herrington et al. 2005) was come out the assumption that the valence of emotions depends on the following ratios of activity left-hand (lfcc) and right-hand (rfcc) frontal cerebral cortex:

$$\text{lfcc} > \text{rfcc} = \text{positive emotions},$$
$$\text{rfcc} > \text{lfcc} = \text{negative emotions}.$$

In the work executed by Gimranov and Kurdyukova (2005) was shown that at activation of the left-hand hemisphere not only increases positive, and at activation of the right –hand a negative sign of emotion, but also there is a decrease in the significance of an emotional sign in a counter cerebral hemisphere that can lead to addition of inequality with the equation of "an emotion conservation law":

$$lfcc(>60\ \%) > rfcc(<40\ \%) = \text{positive emotions},$$
$$rfcc(>60\ \%) > lfcc(<40\ \%) = \text{negative emotions},$$
$$rfcc(40-60\ \%) + lfcc(40-60\ \%) = \text{minimal emotions}.$$

Authors by use of transcranial magnetic stimulation (TMS) confirmed known data that the right-hand hemisphere is more bound with negative, and the left-hand hemisphere with positive emotions. Results of studies of Herrington et al. (2005) and Baumgartner et al. (2011) (as it is described in section "Thermodynamics of framing-effect, intuitive and rational decisions") based on fMRI analysis correlate with the data obtained by Heller (1993), Gimranov and Kurdyukova (2005).

From the standpoint of thermodynamics the results received during research of above mentioned authors, once again testify that after impact on closed system (brain) in this case by use of TMS there is fluctuations which as a result lead system to an equilibrium state and the order is created.

Extrapolating the experimental data, we will receive the following equations: the equation for entropy of a choice of the negative emotions will look as follows:

$$dS = -\sum (Pd) \ln P(d) = -\sum (P1, 2) \ln(P1 + P2) = 0,6 + 0,4 = 1,0;$$

and for entropy of a choice of positive emotions:

$$dS = -\sum (Pd) \ln P(d) = -\sum (P2, 1) \ln(P2 + P1) = 0,6 + 0,4 = 1,0,$$

where P1 = Prfcc, P2 = Plfcc.

Comparing these equations there is also observed effects of the law of conservation of energy, and in this case "an emotion conservation law", which is elegantly agreed with the first law of thermodynamics.

Possible effects of emotion (as function of vector transfer of energy) on decision-making

Emotions influence our belief and informatively influence our decisions; they conduct to our adaptation to the physical and social environment. While at the moment of the greatest conspicuity people are in the situation of big concern, emotions fluctuate even concerning ordinary decisions on which we are focused in an everyday life (Cohen 2005). Considering influence of emotions on a decision making, it was shown, on the one hand, that positive emotions with a large number of perceived alternatives, including a complex of solved strategies, and increase considering time, together with reassessment of possible positive consequences and underestimate probabilities of

negative consequences (Paulus et al. 2005a, b). On the other hand, negative emotions interfere with the fissile searching of alternatives and use of multiple sources of information and they also reduce time necessary for a choice of alternatives (Paulus et al. 2005a, b) Using strategy of induction of mood and estimating desire to make risky decisions (Yuen and Lee 2003) that individuals in induced depression mood were much more conservative in a decision making, than those who were in neutral mood, at the same time, people in induced happy mood slightly differed from those who in neutral mood. Clinical use of these results is obvious when we consider the case of patients with a clinical depression to which often it is recommended by their therapists not to accept critical life decisions since it can make negative impact on affective state in which they are situated.

The behavioral economics and neuroeconomics, unlike traditional economic theories, pays special attention to moral thinking at adoption of economic decisions. Reaction of all people to the main social ethical signals approximately the same, and such state of affairs is norm of human thinking. On this problem interesting works are executed by Paul J. Zak (2004). P. Zac has shown through series of experiments that the human brain possesses "moral feelings" which help to balance between selfish and public interests. These foundations probably explaining moral feelings provides with the neurological base Adam Smith's (2002) point of view which he stated in the "Theories of moral senses" that sympathy or feeling of solidarity is a basis of moral behavior. An important result of these researches is the hypothesis that economic regulation should be moderate as business which swindles or pursues only the selfish aim of a profit at the customer account is self-destructed as clients prefer to deal with the companies which behave morally in relation to the partner. Similar researches were carried out by Delgado et al. (2005) where it is shown that conviction in morally merits of the business partner allows the market player to undertake a risky step.

As it was shown by Ekman's research (2012) and some other scientists, emotions can vary on their force and type. Thus, at systematization of emotions, it is obviously important to consider not only their polarity, but also force and intensity of their affect. These properties are especially important at impact on the individual of a complex of emotions. In case of impact of several emotions equally charging on force, the system will fluctuate at the expense of the competition of equiprobable reciprocal alternatives. Possibly, equal on force, but more intensive emotion will provoke the response decision of the individual, but thus at system there will be dissipation structures which will affect behavior of the person—will provide doubt, uncertainty in a choice of alternative and the accepted decision.

Further emotion will be considered as function of vector transfer of energy in loop system of motion and the analysis of possible alternatives of decision-making.

If we assume that emotion, regardless of its charge, or valence, is an energy source in system, there is possible explanation of a number of phenomena of the human behavior contradicting not simply economic feasibility, but posing threat to a physical survival of the individual.

Still people ask themselves a question how could allow catastrophe and genocide of millions Jews during Second World War? How people, from both parties of a barbed wire didn't resist?

In a situation of low emotional level, for example, depressions, people unable to make decisions, not to mention their usefulness. Examples of decisions, not simply economically unreasonable, but leaders to death—behavior of millions people in captivity.

Fading of emotional life of prisoners in concentration camp with the surgical accuracy deprived of sentimentality, was described by the great psychologist humanist of the twentieth century Frankl (1990). Relying on the personal experience, Frank describes psychological stages which there passed the people who have appeared, as well as him, in the conclusion. The first phase can be characterized as "arrival shock" though, of course, psychologically shock influence of a concentration camp can precede the actual hit in it. Some days later, psychological reactions start to change. Having endured the tentative shock prisoner gradually plunges into the second phase—a phase of the relative apathy when in his soul something dies off. Leaving in itself meant for those who was capable, escape from the sad desert, from spiritual poverty of local existence back, in characteristic own past. The imagination was constantly occupied with restitution of former impressions.

Only having passed through shock and apathy, and having gone deep about characteristic inner world, it was possible to survive. System is characterized by very low level of energy, both physical, and emotional. Based on Viktor Frankl's observation Oettinger and Gollwitzer (2010) have indicated that people can take charge of their everyday life and personal development by effective self-regulation on their goal pursuits.

Similar to Viktor Frankl's feelings are described by another escaped from the imprisonment, the Hungarian writer Kertesz (2004). Its story is based on the same condition of apathy and lack of the strong feelings. The lack of emotions shakes in the story of the former prisoner of concentration camp. "Only in Zeytz I realized that in jail there is also the everyday life; moreover, the real imprisonment is, as a matter of fact, continuous gray everyday life".

Thus, it is possible to assume that emotion is potentially one of the basic catalysts and the inductors of energy inducing the individual, besides a rational assessment to

make solutions of different degree of usefulness and polarity for the person.

Classification of environment in the process of decision-making

As decision-making process directly depends on environment (section "Thermodynamic approach to decision-making process", Fig. 2), we will make also attempt to systematize possible conditions:

1. A decision making in the conditions of definiteness when the data, the problem and the purpose are known precisely—equilibrium state conditions,
2. The decision making in risk conditions when the data can be described by means of stochastic distributions—quasi-stable or slightly disequilibrium state,
3. A decision making in the conditions of uncertainty when the data cannot attribute the relative weights (weight factors) which would represent degree of their importance in decision-making process—bifurcations or periods of strongly disequilibrium states.

Difference between a decision making in the conditions of poorly disequilibrium and strongly disequilibrium states consists that in conditions of indeterminacy random distribution is either unknown, or can't be defined. As a whole, certainly above-mentioned conditions are more peculiar to rational decisions, than intuitive. At the same time, it is impossible to deny importance of a state of environment, its factors in case when game is entered by emotion which can be shown in different degree of intensity depending on environment conditions. It is probable those in the conditions of equilibrium state the vector contribution of emotion will lead to decision-making of higher and more constructive order, unlike process which would flow in bifurcation condition or the period of strongly disequilibrium. In the conditions of indeterminacy of environment, probably emotions which can affect the analysis of alternatives and decision-making are in a situation of equal probabilities that leads system to chaos.

Thermodynamics of framing-effect, intuitive and rational decisions

The situation of achievement of equilibrium can be broken, and the probability of adoption of the inefficient decision can increase under the influence of so-called "framing effect" entered into use by Tversky and Kahneman (1981). The framing effect is semantic manipulation over object of a choice of alternatives by use of various approaches to the situation description. It is apparent that the framing effect changes a vector in choice of alternative of decision-making, entropy also increases and possible probabilities in a choice of alternatives increase. Besides of probable final utility or loss will be perceived differently depending on framing conditions. In case of positive vector of framing with larger probability the leaving tendency from risk will be observed, and in conditions of negative orientation of framing the tendency will considerably changed. A series of graceful experiments of Tversky and Kahneman showed that the direction of the decision depends on a form of statement of a task. Offering examinees the same task formulated either in terms of possible prize, or in terms of possible loss, scientists found out that people aspire to avoid losses even if their decision is irrational and unjustified. It is shown that the person who should choose "smaller from the evils", experiences the strong negative emotions. A subjective significance of loss (or fault) blocks a subjective significance of a similar prize. We conceal in a way to keep internal tranquility and emotional comfort, people prefer not to risk once again, or, in case of impossibility to run away risk, the majority of examinees are declined to unjustified risk hoping to break a big prize and, thereby, to compensate a long emotional discomfort. The problem called "Asian epidemic" became a classical example of the framing effect (Tversky and Kahneman 1981).

Thus, the framing effect introduces additional fluctuating movements in system of alternatives choice, slowing down process, doing it to more chaotic with increase of entropy of loop system. It seems that process of decision-making will go on the way, presented on Fig. 2a which mechanism is described in section "Thermodynamic approach of decision-making process". We believe that framing effect complicating a situation of an unambiguous choice (regardless of its polarity), compels system to pass a threshold of stability and leads it to the nonequilibrium condition. Amplitude of fluctuation increases and all preconditions for considerable production of entropy in system are created. Possibly, entropy distribution in a brain will have the uneven and nonlocal character as growth of entropy will be noted in those zones of a brain in favor of which the vector of possible, but not yet made decision will be focused. As the final choice isn't made, though "sketches of possible decisions" are drawn, there will be choice fluctuations between affective and cognitive (e.g., "paradox of profitability of shares", when investors face a choice between risk and profitability of investments, or in TV game "Deal or No Deal"), moral and rational (e.g., in a task of tram in which the player is offered to push on rails of one person to rescue two). In system dissipative structures are formed and they will exist until the threshold of bifurcation will be overcome and the final choice will be realized. At the same time, production of entropy will increase respectively in those zones of a brain in

which dissipative structures are formed. Entropy growth in system will proceed until full disintegration of dissipative structures.

It is necessary that activity of system with targeted behavior was stronger than activity of habits or automatisms system for adoption of the most optimal decision. Thus, the irrational behavior of the person is explained by the conflict between various systems of determination of subjective utility.

On the other hand, D. Kahneman put forward and proved a hypothesis about dominance of intuitive (System 1) over rational (System 2) decisions. Neuroeconomists with some approximation refer a classical conditioned reflex and accustoming to uniform automatic System 1, whereas targeted behavior (realized through instrumental reflexes) will be a part of the arbitrary System 2.

Ariely (2008) has offered several principles explaining irrational behavior of the person. One of them shows the tendency of the person to adhere to the chosen line of behavior even if this way displays a non-optimal decision.

There was significant for economics result of Kahneman and Tversky researches that the human brain isn't created for the solution of economic problems as preventively is afraid of uncertainty. As a result, the individual at the moment of acceptance insufficiently well-formalized decision intuitively overestimates probability of losses and tries to minimize risk more, rather than that is required by common sense.

Critically considering that inferences concerned mental functions on the basis of neuroimaging data should be made with adequate approximation (Poldrack 2006; Fehr 2012). Neuroimaging data indeed appear to provide valuable evidences for at least parts of local neural networks potentially involved in complex decision making process. Greene et al. (2001) have used fMRI to examine the neural systems that enable moral decision making. They found that reasoning about a variety of moral dilemmas, compared to reasoning about nonmoral dilemmas, activates a network of structures that include the vmPFC. This activation is greater when the moral decision involves negative consequence for another person, compared to when it involves no negative consequence for another person. Naqvi et al. (2006) suggest that moral decisions, compared to nonmoral decisions, engage emotions, especially when one is required to consider the consequences of one's actions for another's well-being. Baumgartner et al. (2011) have found that when fairness and economic self-interest were in conflict, normal subjects (who make costly normative decisions at a much higher frequency) displayed significantly higher activity in, and connectivity between, the right DLPFC and the posterior ventromedial prefrontal cortex (pVMPFC). In contrast, when there was no conflict between fairness and economic self-interest, both types of subjects displayed identical neural patterns and behaved identically. These findings suggest that a parsimonious prefrontal network, the activation of right DLPFC and pVMPFC, and the connectivity between them, facilitates subjects' willingness to incur the cost of normative decisions. Neuroimaging studies definitely provide potentially necessary evidence for the neural elaboration of decision making in the human brain. To understand, however, sufficient aspects of the complex neuro spatio-temporal network dynamics underlying respective decision making processes based on assumptions related to thermodynamic rules, advanced biosignal analysis approaches appear to be necessarily applied (Basar 2005, 2006, 2011). Furthermore, individual aspects such as fluctuations in individual mental strategy have to be considered in trial-by-trial analyses and in an estimation of inter-individuality of the respective brain physiological parameters (Fehr 2012).

Having considered possible mechanisms of a decision making, proceeding from the principles of thermodynamics, here we would like to propose in addition to Kahneman's theory three main systems for discussion: System 1 which is based on an emotional priority, including moral aspect; System 2 which is characterized by rational approach to decision making and System 3 which is based on competition of affective and cognitive approaches in decision making.

The system 1 will be characterized by indeterminacy, short-time decision making which can be risky, inaccurate and unjustified. Being in emotionally excited state, the individual expecting utility of the made decision can face its real uselessness. Due to intuitively made decision the expected result hardly can provoke the true result. Probably, in evolutionary biological, financial economic and social cultural process, decisions which analogically accepted by system 1, further become rational and will result in system 2. The system 2 will differ from system 1 with considerable determinacy, though longer-time process of decision-making as it requires the analysis and logical considering of a situation, calculations and attention, working (Feredoes and Postle 2007), autobiographical (Nurkova 2000) evolutionary, cognitive and some other concerned memories. As the reasonable decision is made,—it runs minimum possible risks and characterized of high degree of utility, justification of expected result. The system 3 is most complex as both emotional and rational components enter into the game. Events can develop in two ways. The first and the most optimal is when emotions elegantly accompany the cognitive decision. The second, catastrophically complex as both components enter fight for a choice. Emotions are capable to sabotage logical sense. In this system it could be reasonable to admit the assumption of LeDoux (1996) concerned possibility to have a safe time due to the emotions which

needs for the analysis of current situation and a probable choice of the most reasonable and adequate decision. Thermodynamic characteristics of all three systems are presented in chapter "Thermodynamic approach to decision-making process".

Conclusions

1. Today there is a methodological gap between the accepted practices of prediction and a decision making assessment, as at individual level or when attempting to predict results of choices of fixed group of people.
2. Attempt to describe probability of decision-making in an indeterminate situation is undertaken by mathematical apparatus of non-linear dynamics. We visually observe that the desirability of acceptance of exact i decision from K alternatives, at the given unit of time, is proportional to the relative attractiveness of i option. The probability of acceptance of this or that decision at the given unit of time is directly proportional to quantity and degree of expressiveness of the emotions accompanying this choice.
3. Applying a thermodynamic approach to decision making system, authors assume that emotion carries out energy function in system, thereby providing possibility of irreversible changes in system and entropy increase. Through fluctuations, being accompanied entropy increase, it is possible to observe achievement of order in systems at any level—from molecular-cellular processes to social changes at larger-scale groups.
4. It is revealed that activation of the left-hand cerebral hemisphere not only increases positive, and at activation of the right-hand cerebral hemisphere—a negative sign of emotion, but also there is a decrease in a significance of emotional sign in a counter cerebral hemisphere that can lead to inequality addition with the equation of "an emotion conservation law". Thus, it might be possible that we can't feel at the same time multidirectional emotions identical on force.
5. Emotions might provide one of the basic catalysts and an inductor of the energy inducing the individual to make solution of different degree of utility and polarity. In situation of the suppressed emotional hum noise the system won't transfer to other condition as there is no source of an internal energy of system.
6. Here it is presented three-modular model of mechanisms of decision-making based on thermodynamic principles covering the following components: affective, cognitive factors and competing between them.
7. The deviation from a rational way of a decision making might become to be logical if we apply a thermodynamic approach to process of individual decision-making. We believe that framing effect, described by Khaneman and Tversky in an indeterminacy situation, could be importing extra fluctuation movements in system of a choice of alternatives, slowing down process, doing it more chaotic with increase of entropy of closed system.
8. Based on thermodynamic approach we propose in this study three systems of choice realization in addition to Kahneman's theory.

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References

Akerlof GA (2001) Behavioral macroeconomics and macroeconomic behavior (The Nobel Prize lecture). The Economic Sciences: 365–366

Ariely D (2008) Predictably irrational: the hidden forces that shape our decisions. Harper Perennial, NY

Basar E (2005) Memory as a "whole brain work": a large-scale model based on "oscillations in supersynergy". Int J Psychophysiol 58:199–226

Basar E (2006) The theory of the whole-brain-work. Int J Psychophysiol 60:133–138

Basar E (2011) Brain-Body-Mind in the nebulous Cartesian system: a holistic approach. Springer, Heidelberg

Baumgartner T, Knoch D, Hotz P, Eisenegger C, Fehr E (2011) Dorsolateral and ventromedial prefrontal cortex orchestrate normative choice. Nat Neurosci 14(11):1468–1476

Camerer CF, Loewenstein G, Prelec D (2004) Neuroeconomics: why economics needs brains. Scand J Econ 106(3):555–579

Cohen JD (2005) The vulcanization of the human brain: a neural perspective on interactions between cognition and emotion. J Econ Perspect 19:3–24

Cohen M et al (2007) Reinforcement learning signals predict future decisions. J Neurosci 27:371–378

Corrado G, Doya K (2007) Understanding neural coding though the model-based analysis of decision making. J Neurosci 27:8178–8180

Damasio A et al (2000) Subcortical and cortical activity during the feeling of self-generates emotions. Nat Neurosci 3:1050–1052

Delgado MR, Frank RH, Phelps EA (2005) Perceptions of moral character modulate the neural systems of reward during the trust game. Nat Neurosci 8(11):1611–1618

Doya K (2008) Modulators of decision making. Nat Neurosci 11(4):410–416

Eddington A (1928) The nature of the physical world. Cambridge University Press, MA

Ekman P (2012) Psychology of emotions. Piter, Moscow

Fehr T (2012) A hybrid model for the neural representation of complex mental processing in the human brain. Cogn Neurodyn. doi:10.1007/s11571-012-9220-2

Feldman J (2012) The neural binding problem(s). Cogn Neurodyn. doi:10.1007/s11571-012-9219-8

Feredoes E, Postle B (2007) Localization of load sensitivity of working memory storage: quantitatively and qualifiedly discrepant results yielded by single-subject and group-averaged approaches to fMRI group analysis. Neuroimage 35:881–903

Frankl V (1990) Man's search for meaning, Progress, Moscow, M

Gimranov RF, Kurdyukova EN (2005) Transcranial magnetic stimulation in research of emotion in the healthy and patients with epilepsy. Zh Vyssh Nerv Deiat Im I P Pavlova 55(2):202–206

Greene JD, Sommerville RB, Nystrom LE, Darley JM, Cohen JD (2001) An fMRI investigation of emotional engagements in moral judgment. Science 293:2105–2108

Gross JJ, Thompson RA (2007) Handbook of emotion regulation. Guilford, London, pp 3–24

Heller W (1993) Neuropsychological mechanisms of individual differences in emotion, personality and arousal. Neurophysiology 7:476–489

Herrington JD, Mohanty A, Koven N, Fisher JE, Stewart JL, Banich M, Webb AG, Miller GA, Heller W (2005) Emotion- modulated performance and activity in left dorsolateral prefrontal cortex. Emotion 5(2):200–207

Hirsh JB, Mar RA, Peterson JB (2012) Physiological entropy: a framework for understanding uncertainty-related anxiety. Psychol Rev 119:304–320

Ikeda T, Hikosaka O (2003) Reward dependent gain and bias of visual responses in primate superior colliculus. Neuron 39:693–700

Izard CE (1977) Human emotions. Plenum Press, New York

Kahneman D (2003) A perspective on judgment and choice: mapping bounded rationality. Am Psychol 58:697–720

Kahneman D, Tversky A (1979) Prospect theory: an analysis of decision under risk. Econometrica 47:263–291

Kahneman D, Tversky A (1984) Choices, values and frames. Am Psychol 39:341–350

Kahneman D, Knetsch JL, Thaler RH (1991) Anomalies: the endowment effect, loss aversion and status quo bias. J Econ Perspect 5:193–206

Kawagoe R, Takikava Y, Hikosaka O (1998) Expectation of reward modulates cognitive signals in the basal ganglia. Nat Neurosci 1: 411–416

Kertesz I (2004) Fatelessness. Knopf, New York, NY

Kondepudi D, Prigogine I (1998) Modern thermodynamics: from heat engines to dissipative structures. Wiley, West Sussex

LeDoux JE (1996) The emotional brain. Simon & Schuster, NY

Lee D, Wang X-J (2008) Neural circuit mechanisms for stochastic decision making in the primate frontal cortex. In: Glimcher PW, Camerer CF, Fehr E, Poldrack RA (eds) Neuroeconomics: decision making and the brain. Academic Press, New York, pp 481–501

Levy WB (1996) A sequence predicting CA3 is a flexible associator that learns and uses context to solve hippocampal-like tasks. Hippocampus 6:579–590

Levy WB, Baxter RA (2002) Energy-efficient neuronal computation via quantal synaptic failures. J Neurosci 22(11):4746–4755

Manski C, McFadden D (1981) Structural analysis of discrete data and econometric applications. The MIT Press, Cambridge

Miller EK, Cohen JD (2001) An integrative theory of prefrontal cortex function. Annu Rev Neurosci 24:167–202

Minamimoto T, Hori Y, Kimura M (2005) Complimentary process to response bias in the centromedian nucleus of the thalamus. Science 308:1798–1801

Naqvi N, Shiv B, Bechara A (2006) The role of emotion in decision making: a cognitive neuroscience perspective. Curr Dir Psychol Sci 15(5):260–264

Nicolis G, Prigogine I (1989) Exploring complexity: an introduction. W. H. Freeman, New York, NY

Nurkova VV (2000) The perfect proceeds. Psychology of autobiographical memory of individual. URAO, Moscow

Nurkova VV, Beresanskaya NB (2010) General psychology. High School, Moscow

O'Doherty J, Hampton A, Kim H (2007) Model-based fMRI and its application to reward learning and decision making. Ann N Y Acad Sci 1104:35–53

Oettinger G, Gollwitzer P (2010) Strategies of setting and implementing goals. In: Maddux JE, Tangney JP (eds) Social psychological foundations of clinical psychology. The Guilford Press, New York

Olsen R (2001) Behavioral finance as science: implications from the research of Paul Slovic. J Behav Financ 2(3):157–159

Pakhomov A, Sudjin N (2012) Emotional aspects of decision-making process: the thermodynamic approach. In: NeuroPsychoEconomics conference proceedings, Erasmus University, Rotterdam, p. 55

Paton JJ, Belova MA, Morrison SE, Salzman CD (2006) The primate amygdale represents the positive and negative value of visual stimuli during learning. Nature 439:865–870

Paulus MP, Tapert SF, Schuckit MA (2005a) Neural activation patterns of methamphetamine: dependent subjects during decision making predict repalse. Arch Gen Psychiatry 62:761–768

Paulus MP, Feinstein JS, Castello G, Simmons AN, Stein MB (2005b) Dose-dependent decrease of activation in bilateral amygdale and insula by lorazepam during emotion processing. Arch Gen Psychiatry 62:282–288

Platt M, Padoa-Schioppa C (2008) Neuronal representations of value. In: Glimcher PW, Camerer CF, Fehr E, Poldrack RA (eds) Neuroeconomics: decision making and the brain. Academic Press, New York, pp 441–462

Poldrack RA (2006) Can cognitive processes be inferred from neuroimaging data? Trends Cogn. Science 10:59–63

Prigogine I, Defay R (1954) Chemical thermodynamics. Longmans Green and Co., London

Prigogine I, Stengers I (1997) The end of certainty: time, chaos and the new laws of nature. Free Press, New York, NY

Raichle M, Gusnard D (2002) Appraising the brain's energy budget. PNAS 99(16):10237–10239

Rangel A, Camerer C, Montague P (2008) A framework for studying the neurobiology of value-based decision making. Nat Rev Neurosci 9:545–556

Roesch MR, Olson CR (2003) Impact of expected reward on neuronal activity in prefrontal cortex, frontal and supplementary eye fields and premotor cortex. J Neurophysiol 90:1766–1789

Rosenbloom MY, Schmahmann JD, Price BH (2012) The functional neuroanatomy of decision-making. J Neuropsychiatry Clin Neurosci 24:266–277

Schultz W (2007) Multiple dopamine functions at different time courses. Ann Rev Neurosci 30:259–288

Sen A (1973) On economic inequality. Norton, New York

Shannon CE, Weawer W (1949) The mathematical theory of communication. University of Illinois Press, Urbana

Simon B, Laughlin I, Sejnowski TJ (2003) Communication in neural networks. Science 5641:1870–1874

Smith A (2002) The theory of moral sentiments. In: Knud Haakonssen (ed) Cambridge University Press, Cambridge

Smith V (2009) Rationality in economics. Cambridge University Press, Cambridge

Stiglitz J, Walsh C (2002) Principles of macroeconomics. W.W. Norton & Company, New York

Stuphorn V, Taylor TL, Schall JD (2000) Performance monitoring by the supplementary eye field. Nature 408:857–860

Tversky A, Kahneman D (1974) Judgment under uncertainty: heuristics and biases. Science 185:1124–1131

Tversky A, Kahneman D (1981) The framing of decisions and the psychology of choice. Science 211:453–458

Volkenstein MV (1986) Entropy and Information. Science, Moscow

Volkenstein MV (1988) Biophysics. Science, Moscow

Wang R, Zhang Z (2006) Mechanism of brain information processing: energy coding. Appl Phys Lett 89:123903

Wang R, Zhang Z (2007) Energy coding in biological neural network. Cogn Neurodyn 1(3):203–212

Wang R, Zhang Z, Chen G (2008) Energy function and energy evolution on neural population. IEEE Trans Neural Netw 19(3): 535–538

Wang R, Zhang Z, Chen G (2009) Energy coding and energy functions for local activities of brain. Neurocomputing 73(1–3): 139–150

Yuen KSL, Lee TMC (2003) Could mood state affect risk-taking decisions? J Affect Disord 75:11–18

Zak Paul J (2004) Neuroeconomics. Philos Trans R Soc B 359: 1737–1748