Fundamental Principles of Neural Organization of Cognition

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Abstract. The manuscript advances a hypothesis that there are few fundamental principles of neural organization of cognition, which explain several wide areas of the cognitive functioning. We summarize the fundamental principles, experimental, theoretical, and modeling evidence for these principles, relate them to hypothetical neural mechanisms, and made a number of predictions. We consider cognitive functioning including concepts, emotions, drives-instincts, learning, "higher" cognitive functions of language, interaction of language and cognition, role of emotions in this interaction, the beautiful, sublime, and music. Among mechanisms of behavior we concentrate on internal actions in the brain, learning and decision making. A number of predictions are made, some of which have been previously formulated and experimentally confirmed, a number of new predictions are made that can be experimentally tested. Is it possible to explain a significant part of workings of the mind from few basic principles, similar to how Newton explained motions of planets? This manuscript summarizes a part of contemporary knowledge toward this goal.

Contents

1. Hypothetical fundamental principles and abilities.

Instinctual drives

Instinctual drives are ancient biological mechanisms. For the purpose of understanding of human cognitive functioning, a significant part of these mechanisms can be modeled by Grossberg-Levine theory of drives and emotions (1987). These authors have modeled an instinctual drive as an internal sensory-like neural mechanism measuring vital bodily parameters. When these parameters are outside safe bounds, the instinctual mechanism sends evaluative neural signals to decision-making parts of the brain.

Emotions

Emotions refer to many different mechanisms in the mind and body. According to (Grossberg & Levine, 1987) emotional signals evaluate concepts for the purpose of instinct satisfaction. Recognition of objects or situations that can potentially satisfy vital needs of the organism (instincts) receive preferential attention. A number of neural and physiological realizations of this mechanism have been identified (Gnadt & Grossberg, 2008).

Concepts

Concepts and perceptions are cognitive mechanisms for understanding reality. Their neural mechanisms are mental representations (Grossberg, 1982, 1988; Kosslyn, 1980, 1994). Some aspects of representations, especially related to early visual perception of objects are retinotopic, other, especially related to abstract concepts are distributed in the brain (Barsalou, 1999).

Top-down and bottom-up signals

Signal streams from sensors to objects, to situations, to abstract concepts are called bottom-up (BU) signals, and signals in the opposite direction, from conceptual representations toward sensor input signals are called top-down (TD) signals. Representations at a higher level create more abstract concepts as collections of lower level ones. Many neural pathways in the brain carry neural connections in reciprocal directions (Grossberg, 1988).

Learning in interaction of TD and BU signal

The fundamental mechanism of learning representations is an interaction between BU and TD. In interaction of the two nearby layers BU signals project to a higher level sensor signals, or signals from identified representations at a given layer. At the same time TD signals project expected representations from the higher layer down to the lower one. Modeling this interaction is fundamental for understanding learning mechanisms.

Vague-to-Crisp process of learning

Interaction of BU and TD signals proceeds from initial vague representations to crisp (or crisper) representations. This process from vague to crisp is hypothesized to be fundamental for many brain mechanisms, including cognition-language interaction. Mathematical model of this process, dynamic logic, has been developed for overcoming a fundamental difficulty of modeling the mind in artificial intelligence, complexity of computation (Perlovsky 1987, 2001, 2006a). This complexity is related to using logic for modeling the mind. Complexity of logical models of cognition and perception exceeds by far all interactions of all particles in the Universe during its entire lifetime. Bar et al (2006) demonstrated that a vague-to-crisp process is a valid model for visual perception, which proceeds as the process from vague to crisp. Starting with vague representations eliminates the need to consider combinations of objects and results in low computational complexity, corresponding to actual cognitive processes.

Consciousness, unconscious, and logic

Crisp-logical or nearly logical brain states are available to consciousness. Vague states and processes are not available to consciousness (Perlovsky, 2001, 2006; Bar et al, 2006). Because of this, consciousness and subjective intuition are biased towards logic. This bias affects scientists as well; therefore most scientific ideas and cognitive theories are biased toward logic and may lead to contradictions (Perlovsky, 2006, 2011a, 2012a). Representations at higher levels are built on top of several lower levels. Correspondingly they are vaguer and less conscious.

Knowledge instinct

Understanding reality requires matching BU and TD signals. Without this match mental representations would not correspond to objects and situations. Therefore higher animals and humans are endowed with inborn unconscious drive to match BU and TD signals. This match is a measure of knowledge, therefore this instinctual drive is called the knowledge instinct, KI, (Perlovsky 2001, 2006). Hypothetical neural mechanisms of KI have been considered in (Levine & Perlovsky 2008, 2010).

Aesthetic emotions

According to drive and emotion theory (Grossberg & Levine, 1987) satisfaction of every instinct-drive is experienced emotionally. Satisfaction (or dissatisfaction) of KI is experienced as special emotions (Perlovsky, 2001, 2006; Perlovsky, Bonniot-Cabanac, & Cabanac, 2010); because they are related to knowledge, these emotions are called aesthetic emotions (Kant, 1790). They are “higher” then emotions corresponding to bodily instinctual needs. At lower hierarchical levels they reach consciousness usually when KI is dissatisfied, as in horror movies. At higher levels positive aesthetic emotions could be conscious. It follows that cognition combines conceptual and emotional mechanisms.

2. Cognitive abilities explained from fundamental principles

Hierarchy

The mind-brain is organized in an approximate hierarchy from sensory signals, to early processing mechanisms producing sensory “features,” to objects, contexts, scenes, situations, and higher up to representations of abstract concepts, and to even higher abstractions, which contents we consider later (Grossberg, 1982, 1988). Lower-levels of hierarchy, from sensor signals to objects exist in higher animals and are of genetic origin. Hierarchy above objects sets humans aside from animals; its emergence requires language and the process from vague to crisp, as discussed below.

Language

Language is a hierarchy parallel and similar to cognition. Driven by language instinct (LI), language is learned by about the age of five. This is possible because LI drives language representations to match surrounding language, but not the real life. Surrounding language contains words, phrases, grammar “ready made” throughout the entire hierarchy. This is a fundamental difference between language and cognition. Objects and concepts of cognition, especially higher in the hierarchy, do not exist “ready made” in the surrounding world. Therefore cognition takes a lifetime. Matching language representations to surrounding language involves BU and TD signal interaction and processes from vague to crisp discussed earlier (Perlovsky, 2009a).

Dual hierarchy of interacting language and cognition

The brain-mind contains two parallel hierarchies of cognitive and language representations (Perlovsky, 2004, 2009a, 2010e). In the inborn mind, both types of representations are vague placeholders for future contents, but neural connections between representations are inborn. Both representations are becoming crisp in the process from vague to crisp discussed earlier. By about age of five, language representations are crisp, conscious, and correspond to surrounding language. Most of cognitive representations are vague and unconscious. Throughout the rest of life, cognitive representations acquire more concrete contents in correspondence with one's experience and contents of language representations, neurally connected to each cognitive representation. This explains first, how the hierarchy of cognitive representations can be learned on top of vaguer and vaguer representations, language serves as a scaffold. Second, this explains how every child manages to connect words and objects correctly among virtual infinity of incorrect associations. Third, it explains why children can clearly and logically talk about almost everything, but cannot act like adults: their cognitive representations (about the world) are vague and unconscious. Fourth, it gives a plausible hypothesis of language evolution: necessary neural wirings connecting the two types of representations have long been there due to the mirror neuron system (Rizzolatti & Arbib, 1998; Arbib, 2005; Perlovsky, 2012d).

Beautiful, sublime, and the meaning of life

Representations at higher levels of the hierarchy evolved to unify entire experience (partially in genetic evolution and partially in cultural evolution). They are felt as the meaning and purpose of life. Satisfaction of KI at these high levels is experienced as emotions of the beautiful. Aesthetic emotions at these high levels, when related to representations of behavior that could realize the purpose and meaning in ones life, are experienced as emotions of the sublime, a foundation of all religions (subjectively unconscious). Cognitive representations at these high levels of the mental hierarchy are mostly inaccessible to consciousness. The dual hierarchy explains why it is possible to talk crisply and logically about the meaning and purpose of life, the beautiful and sublime (because language representations are crisp and logical throughout the entire hierarchy), whereas it is not possible to achieve final and logical understanding of the meaning of life or formulate rules of the beautiful (Perlovsky, 2000, 2001, 2001, 2006a, 2010b,f,g). When one feels logical and conscious understanding of these issues, this understanding is similar to children's understanding: language representations are crisp and conscious, but cognitive representations are vague and unconscious.

Language evolution

Conceptual and emotional contents in animal's vocalizations are inseparable. Also, vocalizations in animals are inseparable from conceptual-emotional-behavioral mental states. Vocal chords are controlled from ancient involuntary emotional centers in limbic system. Evolution of language required freeing vocalizations from uncontrollable emotional encumbrances. This required rewiring of the brain and evolution of emotional centers in cortex, partially under volitional control, which could consciously control vocalization (Deacon, 1989; Lieberman, 2000; Mithen, 2007, Botha, 2003; Botha & Knight 2009).

Language emotionality

Emotionality of all human languages is significantly reduced as compared to animal vocalizations. All humans have significant control over emotionality of vocalizations. Still some degree of emotionality is necessary to motivate connecting language representations to cognitive representations (Perlovsky, 2007a, 2009b, 2010a,e, 2012b,e).

Language and culture. Emotional Sapir-Whorf hypothesis

Efficient dual hierarchy of language and cognition requires "appropriate" emotionality of human voice (Perlovsky 2007a). Low emotionality helps fast evolution of conceptual knowledge, but threatens connection between knowledge and values. Psychological well-being is not automatically guaranteed. The entire culture might lose its meaning and purpose. High emotionality makes conceptual knowledge highly valuable and difficult to modify. Individual psychological well-being is "automatic," but conceptual knowledge evolves slowly, culture stagnates. Language emotionality has been connected to language grammar (Perlovsky 2009b, 2011b, 2012b).

Cognitive dissonance

Language helps evolving diverse knowledge. This has to lead to multiple cognitive dissonances (CD), contradictions in knowledge. CD are difficult to tolerate and human tend to dismiss contradictory knowledge (devalue contradictory knowledge, often irrationally). The 2002 Nobel Prize in economics (Kahneman) has been awarded to significant extent for recognition that CD may cause irrational decisions (Tversky and Kahneman, 1974).

Music

CD during emergence of language would cause devaluing contradictory knowledge. Every knowledge contradicts, to some extent, inborn drives and other knowledge (otherwise this new knowledge will not be needed). Therefore CD during emergence of language would devalue knowledge, language, cognition, evolution of consciousness. Human cultural evolution required a powerful mechanism for resolving CD. In animals, conceptual and emotional parts of vocalization are fused, and CD does not appear in natural states. Therefore, evolution of language toward less emotionality of vocalization had to be accompanied by evolution of emotional part of vocalization toward enhanced emotionality, helping mitigate CD. Many evolutionary scientists assumed that initially language and music have been fused. Eventually emotionality of voice evolved into music. This is the cognitive function of music, the reason for its evolution, which has been considered mysterious by Aristotle, Kant, Darwin, and by contemporary evolutionary psychologists and musicologists (see reviews in Perlovsky, 2006c, 2008, 2010a, 2012c,e,f).

3. Experimental, theoretical, and model arguments

TD and BU signals, vague-to-crisp process, dynamic logic, consciousness, and unconscious

Since the 1950s artificial intelligence attempted to model cognitive processes of perception. The encountered difficulties have been related to combinatorial complexity (CC) of computations

(Perlovsky, 1997, 1998). These were related to Gödelian limitations of logic; they were manifestations of logic inconsistency in finite systems (Perlovsky 2001). To overcome limitations of logic, dynamic logic was proposed (Perlovsky 1991, 2001, 2006a). Whereas logic works with statements (e.g. “this is a chair”), dynamic logic is a process from vague to crisp, from a vague statement, decision, plan, to crisp ones. A large number of engineering problems have been solved with dynamic logic, which remained unsolved for decades (Perlovsky 1987; Perlovsky, Deming, & Ilin, 2011 and refs therein).

Consider a seemingly simple experiment. Close your eyes and imagine an object in front of you. The imagined image is vague, not as crisp and clear as with opened eyes. As we open our eyes; the object becomes crisp and clear. It seems to occur momentarily, but actually it takes 1/5th of a second. This is a very long time for neural brain mechanisms – hundreds of thousands of neural interactions. Let us also note: with opened eyes we are not conscious about the initially vague imagination, we are not conscious of the entire 1/5th of a second, we are conscious only about the end of this process: a crisp, clear object in front of our eyes. The explanation of this experiment has become simple after many years of research that have uncovered what goes on in the brain during these 1/5th of a second.

Dynamic logic corresponds to the open-close eye experiment: initial states of the models are vague. This experiment was performed measuring many details using brain imaging. M. Bar, K. S. Kassam, A .S. Ghuman, J. Boshyan, A. M. Schmid, A. M. Dale, M. S. Hamalainen, K. Marinkovic, D. L. Schacter, B. R. Rosen, and E. Halgren (2006) used functional Magnetic Resonance Imaging (fMRI) to obtain high-spatial resolution of processes in the brain, which they combined with magneto-encephalography (MEG), measurements of the magnetic field next to head, which provided a high temporal resolution of the brain activity. Combining these two techniques the experimenters were able to measure high resolution of cognitive processes in space and time. Bar et al concentrated on three brain areas: early visual cortex, object recognition area (fusiform gyrus), and object-information semantic processing area (OFC). They demonstrated that OFC is activated 130 ms after the visual cortex, but 50 ms before object recognition area. This suggests that OFC represents the cortical source of top-down facilitation in visual object recognition. This top-down facilitation was unconscious. In addition they demonstrated that the imagined perception generated by the top-down signals facilitated from OFC to the cortex is vague, similar to the close-open-eye experiment. Conscious perception of an object occurs when vague projections become crisp and match a crisp image from the retina, following that an object recognition area is activated.

The opened-closed eye experiment confirmes that crisp-logical or nearly logical brain states are available to consciousness. Vague states and processes are not available to consciousness (Perlovsky, 2001, 2006; Bar et al, 2006). Because of this, consciousness and subjective intuition are biased towards logic. This bias affects scientists as well; therefore most scientific ideas and cognitive theories are biased toward logic and may lead to contradictions (Perlovsky, 2006, 2011a, 2012a).

Knowledge instinct and aesthetic emotions

Hypothetical neural mechanisms of KI have been considered in (Levine & Perlovsky 2008, 2010). Satisfaction (or dissatisfaction) of KI is experienced as aesthetic emotions (Perlovsky, 2001, 2006a). Existence of these emotions have been experimentally demonstrated in (Perlovsky, Bonniot-Cabanac, & Cabanac, 2010).

Dual hierarchy of interacting language and cognition

Initial experimental indication for the dual model has appeared in (Franklin, A., Drivonikou, G. V., Bevis, L., Davie, I. R. L., Kay, P. & Regier, T. 2008). They have demonstrated that the categorical perception of color in prelinguistic infants is based in the right brain hemisphere. As language is acquired and access to lexical color codes becomes more automatic, categorical perception of color moves to the left hemisphere (between two and five years) and adult's categorical perception of color is only based in the left hemisphere. These experiments have provided evidence for neural connections between perception and language, a foundation of the dual model. Possibly it confirms another aspect of the dual model: the crisp and conscious language part of the model hides from our consciousness the vaguer cognitive part of the model. This is similar to what we observed in the close-open eye experiment: with opened eyes we are not conscious about vague imaginations-priming signals.

Language emotionality and cultural evolutions. Emotional Sapir-Whorf hypothesis

Different emotionalities of different languages have been experimentally demonstrated in (Guttfreund, 1990; Harris, Ayçiçegi, & Gleason, 2003). In particular, experimental results of (Guttfreund, 1990) suggest that emotionality is a property of languages, not effects of cultures on languages. Different cultural historical paths influenced by languages have been considered in (Perlovsky, 2007a, 2009b).

Music reduces cognitive dissonance

In Masataka and Perlovsky (2012) it has been experimentally demonstrated that music reduces cognitive dissonance. This publication repeated a classical experiment known to induce CD and the corresponding devaluation of the contradictory objects. When the same experiment has been repeated with music, devaluation did not occur. The music used in this experiment is known to lead to mental excitation, not relaxation. It is concluded that CD actually occurred, and music helped to keep contradictory knowledge, rather than discarding it.

4. Experimentally testable predictions

Vague-to-Crisp process in the hierarchy; consciousness and unconscious

Vague-to-crisp process of learning is predicted as fundamental by dynamic logic. Consciousness of crisp states and unconsciousness of the process from vague to crisp is predicted. These predictions have to be experimentally demonstrated higher up in the hierarchy, in interaction between cognition and language and in every learning process.

Aesthetic emotions

Aesthetic emotions have been experimentally demonstrated in (Perlovsky, Bonniot-Cabanac, & Cabanac, 2010). These initial demonstrations have to be repeated in various settings. Satisfaction of KI has to be experimentally related to the meaning of life, beautiful and sublime emotions.

Dual hierarchy of interacting language and cognition

Experimental demonstrations are needed to prove that language and cognition interact as predicted by the dual model. Neural connections between language and cognitive representations should be demonstrated. Another prediction of the dual model is that when talking (discussing, reading) about abstract and less known concepts, cognitive representations are less excited than when discussing everyday well-known topics. This effect in adults should be compared to the one in children.

Beautiful, sublime, and the meaning of life

Is it possible to demonstrate language rather then cognitive understanding of representations at the top of the mental hierarchy?

Language emotionality

Initial research on emotionalities of various languages demonstrated in (Guttfreund, 1990; Harris, Ayçiçegi, & Gleason, 2003) should be continued. Complex relations between conceptual and emotional contents of various languages should be experimentally explored. Language emotionality and grammar should be correlated (Perlovsky 2009b, 2011b, 2012b).

Language and culture. Emotional Sapir-Whorf hypothesis

Language emotionalities, grammars, and cultural evolutionary paths should be empirically studied (Perlovsky 2009b, 2011b, 2012b). Some correlations are obvious, but scientific data are very limited.

Cognitive dissonances

Although CD is a well studied field, still more remains to be done. Emotions of CD should be "instrumentalized." Only few basic emotions, which can be named by emotional words, have been studied and the number of independent emotions has been identified (few). Basic emotions are similar for humans and animals. The real wealth of human emotions has not even been discussed. Existence of CD emotions should be demonstrated. The number of CD emotions (likely very large) should be demonstrated (Perlovsky, 2006c, 2008, 2010a, 2012c,e,f).

Music

The initial results on music ability to help mitigating cognitive dissonances (Masataka & Perlovsky 2012) should be continued. A number of predictions about music (Perlovsky, 2006c, 2008, 2010a, 2012c,e,f) is a vast field for experimental studies. These include: the number of musical emotions (very large, practically infinite); relations between emotions in music and CD, which music helps reducing which CD; relations between emotionality of languages and musical emotions in various cultures; is a large number of pop-songs in English a cultural compensation for low emotionality of English language?

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