Creativity and the Brain

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Abstract. Neurocognitive approach to higher cognitive functions that bridges the gap between psychological and neural level of description is introduced. Relevant facts about the brain, working memory and representation of symbols in the brain are summarized. Putative brain processes responsible for problem solving, intuition, skill learning and automatization are described. The role of non-dominant brain hemisphere in solving problems requiring insight is conjectured. Two factors seem to be essential for creativity: imagination constrained by experience, and filtering that selects most interesting solutions. Experiments with paired words association are analyzed in details and evidence for stochastic resonance effects is found. Brain activity in the process of invention of novel words is proposed as the simplest way to understand creativity using experimental and computational means. Perspectives on computational models of creativity are discussed.

1. Introduction

The mystery of the mind and its relations to the brain is slowly being unraveled. Many low-level cognitive functions involving perception and motor control have reasonable neural models. For example, deficits in quantization of basic speech sounds (phonemes) lead to phonological dyslexia and thus learning problems. Despite great progress in neuroscience higher cognitive functions: language, thinking, reasoning, planning, problem solving, understanding of visual scenes, are all poorly understood. Creativity seems to be one of the most mysterious aspects of the human mind and any attempt to elucidate brain processes behind creative thinking at present has to be speculative. Nevertheless, despite the limitation of the current knowledge of the neural processes that give rise to the cognitive processes in the brain it is possible to propose a testable, neurocognitive model of higher cognitive functions including creative processes.

Creativity research is still in the domain of philosophers, educators and psychologists, as can be seen from articles in *Creativity Research Journal* and *Journal of Creative Behavior*. The *Encyclopedia of Creativity* [1], with articles written by 167 experts, has a few articles (by Goswami, Pribram, Proctor and Schuldberg) concerning general brain processes, quantum phenomena, chaos and dynamical systems. These articles do not propose testable neurological or computational models of creativity. In theoretical cognitive science the metaphor of "a brain as a computer" is still dominating. The *MIT Encyclopedia of Cognitive*

Sciences [2] devotes only two pages to creativity, does not mention intuition at all, but has 6 articles devoted to logic, mentioning different kinds of logic in the index almost 100 times. This overemphasis of logic is rather strange because most cognitive functions, such as understanding visual scenes, emotional states of people or creative thinking obviously cannot be reduced to logical operations. There are several reasons for this situation: early models of brain functions have been based on logic; artificial intelligence has focused only on symbol manipulation for problem solving; computational functionalism in philosophy of mind separated neural and mental processes focusing on conceptual analysis of thinking processes. Once the theory has been established it was much easier to extend it than to develop new approaches that usually require new concepts and ways of thinking.

This situation begun to change with the introduction of dynamical systems as a language suitable for description of early motor and cognitive development [3]-[5]. Symbolic language may provide only an awkward approximation to continuous motor processes (movement of limbs, reaching, crawling, posture development). Introduction of mathematical language of dynamical systems allowed for more precise approximation and categorization of different stages of development, including concept formation based on sensory motor coordination. Perception, action and cognition are all seen as spatio-temporal (behavioral) pattern formation, self-organization of emobodied and situated complex systems. At the level of higher cognitive processes pattern formation in the brain is very rapid, with words and concepts labeling the action-perception subnetworks [6][7].

A neurocognitive model of brain processes that would bridge the gap between psychological and neural level of description is urgently needed to make progress in creativity research. It should link low-level and higher-level cognitive processes, and allow for analysis of relations between mental objects, showing how neurodynamical processes are manifested in inner experience at the psychological level. This seems to be a very difficult venture as the language of neuroscience and the language of psychology are quite different. Some experts believe that the gap between mind and body is so huge that it can never be solved (see for example [8] and the discussion following this paper). A fruitful way to look at this problem [9] is to start with the neurodynamical description of brain processes and look for approximations to the evolution of brain states in low-dimensional space where each dimension may be related to inner experience. Similar approach has been quite successful in elucidation of movement patterns, where large brain areas act in a cooperative way to produce simple movements of fingers or limbs [5]; description of brain processes behind movement control can then be done in low-dimensional spaces. This idea has been used to model category learning in experimental psychology, showing why counter-intuitive answers may be given in some situations [10]. On the surface many contradictory psychological explanations for such experiments may be invented, but they all are based on wrong understanding of causes that are responsible for brain decisions in such situations.

A brief introduction to the neurocognitive understanding of higher cognitive functions is presented in the next section. This is followed by description of the use of words and symbols, putative brain processes responsible for creativity, and analysis of experiments on pairwise word associations by creative and less creative people. Neurocognitive approach is then applied to one of the simplest domain where creativity is manifested: invention of new, interesting words. It is suggested that this could be a good area for more precise tests of creative processes at the computational, psychological and brain imaging and electrophysiology levels. Discussion of the results and future directions of the neurocognitive approach to creativity closes this paper.

2. Neurocognitive approach to higher cognitive functions

Human behavior is a result of extremely large-scale neurodynamics, or continuous changes in the activation state of a large number of brain areas. Infants and babies develop intuitive theories about physical world and minds of people [11]. A rough approximation to the brain processes involved in formation of knowledge about the world is provided by causal Bayesian networks. Even young children seem to be able to learn conditional probabilities from observed patterns of their own actions and human interventions that change the situation [12]. This is certainly an interesting direction although systematic approximations to neural processes that will lead to Bayesian networks have not yet been demonstrated. The innate need to understand the world, including results of ones own actions, leads to narrative comments on one's own behavior, sometimes to rationalization and confabulation [13].

2.1 Few facts about the brain

The brain is not a general purpose computer, it is more a highly specialized device that offers a large number of automatic responses that are used in an adaptive way as a result of learning. A few general statements about the brain follows below, some of them established quite well, and some of them still rather speculative.

- The overall level of arousal and awareness is determined by the reticular formation in the brain stem.
- Many important neurotransmitters are produced in the brain stem, including serotonin (raphe nuclei) and norepinephrine (locus ceruleus).
- Brain stem may be responsible for selection of the global behavioral state, activating and inhibiting different brain areas [14], with more precise selection of actions done by basal ganglia.
- Reward information is used to choose, learn, prepare and execute goal-directed behavior, mediated by dopamine neurotransmitters produced mostly in the midbrain ventral tegmentum area, medial temporal cortex involved in the detection and prediction of rewards, and orbitofrontal cortex and amygdala that evaluate relative reward values and expectations [15]-[17].
- Representation of goals is maintained in parietal, premotor and dorsolateral prefrontal cortex [17].
- Motivation, resulting from anticipation of rewards or conditioned positive emotions, is correlated with activity of ventral striatum.
- Executive functions, such as planning, reasoning, abstraction, initiation and disinhibition of behaviors, are strongly correlated with results of verbal and visual memory tests and with the IQ tests [18].

- Working memory [19] has a very limited capacity of only 3-4 visual objects [19], and about 4 chunks of information [21].
- A distinct verbal working memory system is used by the brain to analyze the syntactic structure of a sentence and determining its meaning [22].

2.2. Working memory

Current working memory model of Baddley [19] includes central executive functions in the frontal lobes, focusing, switching and dividing attention, and providing an interface to the long-term associative memory via episodic memory buffer. In this model working memory includes also two slave short-term memory buffers, auditory phonological loop and visuospatial sketchpad. Individual differences in the ability to control attention depend on the working memory capacity [21] and are obviously reflected in the ability to solve problems and exhibit intelligent behavior. Electrophysiological and brain imaging studies show the involvement of frontal, temporal and parietal associative cortex in storage of working memory information. However, it is quite likely that working memory is not a separate subsystem, but simply an active part of the long-term memory (LTM) network (see the review of the evidence for this point of view in [23]) due to priming and spreading of neural activation. The same brain regions are involved in perception, storage and re-activation of LTM representations. Some activated LTM subnetworks may be in the focus of attention of the central executive (presumable this is the part we are conscious of) and some may be activated but outside of this focus.

Sensory systems transform the incoming stimuli extracting from auditory and visual streams basic quantized elements, such as phonemes or edges with high contrast. These elementary building blocks form larger patterns, building discrete representations for words and shapes. Although gross brain structures are identical in all normal infants there is a lot of variability at the microscale that may result in exceptional talents or developmental disorders. Auditory event-related potentials (ERPs) for consonant sounds, recorded from left or right hemisphere less than two days after birth, predicted with over 80% accuracy the level of reading performance of children eight years later [24][25]. Lack of systematic perceptual training of infants leaves the developmental process at mercy of random influences, resulting in frequent speech, hearing and reading problems.

2.3. Symbols in the brain

To understand the higher cognitive processes one should start from representation of symbols in the brain. Cortex has layered modular structure, with columns of about 10^5 densely interconnected neurons, communicating with other cortical columns in the neighborhood and sometimes also in quite distant areas across the brain, including the opposite hemisphere. Each column contains thousands of microcircuits with different properties (due to the different type of neurons, neurotransmitters and neuromodulators), acting as local resonators that may respond to the sensory signals converting them into intricate patterns of excitations. Genetic code does not contain sufficient information to specify the details of all local connections in cortical columns, but their great complexity and randomness may actually help to create unique, individual activity patterns that are relatively easy to recognize by other brain areas. Hearing words activates a strongly linked subnetwork of microcircuits that bind articulatory and acoustic representation of a spoken word.

Such patterns of activation are localized in most brains in the left temporal cortex, with different word categories coded in anterior and posterior parts [28][29]. The ability to hear and recognize a word does not imply that it can be properly pronounced. Production of words requires precise motor programs that are linked to phonological representations in temporal cortex, but are stored in frontal motor cortex (Brocka's area), connected to the temporal areas via a bundle of nerve fibers called the *arcuate fasciculus*. Damages (lesions) to this fiber or to the cortex processing auditory and language-related information leads to many forms of aphasia [30].

Words are organized in a lexicon, with similar phonological forms activating adjacent resonant microcircuits. Upon hearing a word string of connected resonators is activated, creating representation of a series of phonemes that is categorized as a word (Fig. 1). Native language has a number of syllables and longer chunks of sounds (morphemes) that get easily activated when only part of the word is heard. As a result hearing is more robust (in a noisy environment) but frequency effects may sometimes lead to activation of wrong representations. For example, my first name Wlodzislaw is often written down as a much more common name Wlodzimierz by native Polish speakers, because the first half "Wlodzi" is rather unique and almost always followed by "mierz". Foreign speakers do not hear it properly because phonological representations of some sounds, such as "dz" are very weakly connected in their brain, and therefore it frequently gets misspelled in all possible ways.

Psycholinguistic experiments show that acoustic speech input is quickly changed into categorical, phonological representation. A small set of phonemes, quantized building blocks of phonological representations is linked together in an ordered string by a resonant state representing word form, and extended to include other microcircuits defining semantic concept. From the N200 feature of event-related potentials it has been conjectured that phonological processing precedes semantic activations by about 90 ms [26].

Phonological representation activate an extended network that binds symbols with related perceptions and actions, grounding the meaning of the word in a perception/action network. Various neuroimaging techniques confirm existence of semantically extended phonological networks, giving this model of word representation strong experimental support [26][27]. Symbols in the brain are thus composed of several representations: how they sound like, how to say them, what visual and motor associations they have. This encoding automatically assures that many similarity relations, phonological as well as semantic, between words may automatically be retrieved. Meanings are stored as activations of associative subnetworks that may be categorized and processed further by other areas of the brain. Hearing a word activates string of phonemes increasing the activity (priming) of all candidate words and non-word combinations (good computational models of such phenomena in phonetics are described in [31][32]). Polysemic words probably have a single phonological representation that differs only by their semantic extensions. Context priming selects extended subnetwork corresponding to a unique word meaning, while competition and inhibition in the winner-takes-all processes leaves only the most active candidate networks. The subtle meaning of a concept, as stored in dictionaries, can only be approximate, as it is always modified by the context. Overlapping patterns of brain activations for subnetworks coding word representations lead to strong transition probabilities between these words and thus semantic and phonological associations that easily "come to mind".

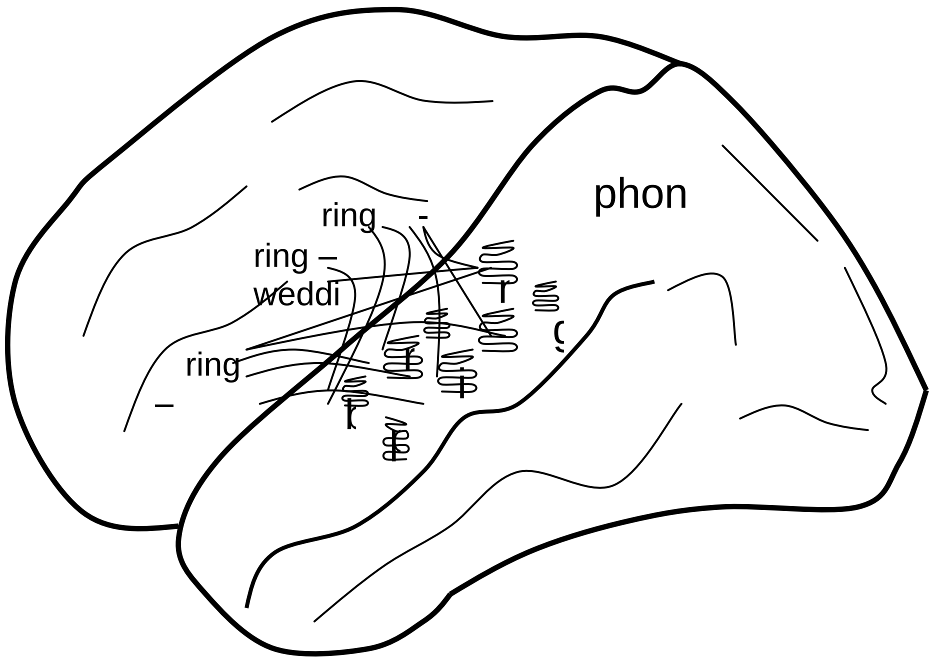

Fig. 1. Listing to a word activates phonological representation and primes extened subnetworks that encode semantic representaiton binding perceptual and motor areas.

Perception/action networks allow for associative learning of simple facts and behavioral rules. To recognize a word in a conscious way activity of its subnetwork must win a competition for an access to the working memory [33]. In the language of dynamical systems memory traces are coded by attractor states binding activity of microcircuits in many minicolumns that code elementary features derived from sensory inputs. These processes cannot easily be approximated by simple behavioral rules. Analysis of real data shows that only a simple reasoning may be based on logic and justified using comprehensible rules that can be expressed in symbolic language [34][35]. Intuitive reasoning based on similarity to previously observed cases can sometimes be expressed using fuzzy rules [36]. In many cases the brain may take intuitive decisions evaluating complex similarity patterns – activation patterns of cortical networks in posterior sensory and associative cortex will automatically be perceived by the working memory executive frontal lobe areas as similar, because information carried over such long distances in the brain is not too precise. The number of logical rules required to justify some decisions based on intuition may be impractically large. Explanation of intuition is thus rather simple.

2.4. Problem solving

A model of intuitive problem solving with concepts defined by probability density distributions over combinations of activations representing feature values in psychological spaces has been presented in [37]. This model has been applied to problem solving, learning in a qualitative way (from observations) Ohm's and Kirchoff's laws, and answering questions about the current and voltage changes in a simple electric circuit without solving any equations. General problem solving process involves the following steps:

1. Stating the problem by reading, listening or thinking about it puts it into working memory, that is activates (primes) different elements of the long-term memory and indirectly (through attention) binds them together.
2. Activation is spread and associated memory elements activated; this may be interpreted as inferences made by specialized processors that can handle bits and pieces of the problem [38].
3. New activations are recognized by the central executive as useful steps towards solution, thus changing the problem state; this cycle is repeated until a solution is found or an impasse is reached.
4. Final solution is a series of associations that lead from the initial brain state – problem statement – to the final state, representing problem solution.

Several things should contribute to efficient problem solving. First, the information must really be in the working memory. Thus the ability to pay attention, focus on the problem and inhibit irrelevant brain process is important. The problem is easy if relevant features are extracted and associations are quickly formed, as it happens if similar problems have been solved many times. Understanding of basic concepts is equivalent to placing them in the web of associations, using chunks of knowledge that cannot easily be replaced by elaborate reasoning, learning symbol manipulations, that is forming strong associations between different concept representations that automatically and effortlessly lead from one brain state to the other.

If the problem is hard associations will not be formed quickly; long priming (persistent thinking about the problem), activation of appropriate brain areas by looking at similar problems or by considering subproblems, may be helpful. General arousal of the brain, increasing the oxygen supply (deep breathing, taking a walk), or playing background instrumental music (hearing words may be disruptive) to increase activation could help. If an impasse is reached some chunk of knowledge may be missing, therefore intermediate associations should be searched for, or simplified (abstract) version of the problem should be considered.

2.5. Skill learning

When new skills are learned initially they demand full conscious attention and eventually become fully automatic, subconscious actions. This is one of the most mysterious processes that may shed some light on the nature of consciousness. Without going into the controversies surrounding consciousness itself, one may assume that in the course of skill learning the focus of attention gradually shifts from elements of the task being learned stored in the working memory that do not need anymore corrections, to other perceptual and internal processes that require attention. This is due to the interplay between the working memory (frontal lobes), intermediate memory storage and value-meaning associations based on the activity of the old memory system in hippocampus and emotional memory in amygdala, long term memory storage (associative cortex), learning of motor sequences (basal ganglia, caudate and putamen nuclei, pre-motor and supplementary motor cortex), as well as further improvements of initial skills due to cerebellar learning and interaction with the sensory cortices (including proprioception) providing the input. The skill learning process may be divided into 3 stages:

1) In the cognitive stage, initial (usually verbal) characterization of the skill is used to guide the behavior. Understanding instructions requires the use of working memory (frontal cortex), intermediate memory (hippocampus) and spatial imagination (parietal cortex).

2) In the associative stage, motor actions are produced (motor cortex) and consequences are evaluated matching results with expectations (sensory and limbic areas), with reinforcement learning tuning the behavior, eliminating errors and the need for verbal mediation and attention to basic movements.

3) In the autonomous stage, the skill is gradually improved via cerebellar learning making fine corrections to motor control signals, with little reliance upon working memory.

Skill learning is obviously a complex activity, still controversial and perhaps too complex to create detailed computational simulations. How is this neurocognitive account of higher cognitive functions related to creativity?

3. Creativity from psychological and neurocognitive perspective

Creativity has been defined by Sternberg [39] as “the capacity to create a solution that is both novel and appropriate”. Creativity manifests itself not only in creation of novel theories or inventions, but permeates our everyday actions, understanding of language and interactions among people. This becomes clear when simulation of human behavior by chatterbots, avatars, and robots is attempted. Intelligence is strongly correlated with creativity and it is quite likely that both have similar neurobiological basis. The g-factor is highly correlated with working memory capacity, perceptual speed, choice and discrimination reaction times, the structure of EEG event-related potentials (ERP potentials), nerve conduction velocity, and cerebral glucose metabolic rate during cognitive activity [40]. Brains of creative and intelligent people probably differ in the density of synaptic connections, contributing to the richer structure of associations, and more complex waveforms of the ERP potentials.

3.1. Creativity and brain networks

Problems that require creativity are difficult to solve because neural circuits representing object features and variables that characterize the problem have only weak connections, and the probability of forming appropriate sequence of cortical activities is very small. The preparatory period introduces all relevant information, activating corresponding neural circuits in the language areas of the dominant temporal lobe, and recruiting other circuits in the visual, auditory, somatosensory and motor areas used in extended representations. These brain subnetworks are now “primed”, and being highly active reinforce mutually their activity, forming many transient configurations and inhibiting at the same time other activations. Difficult problems require long incubation periods that may be followed by an impasse and despair period, when inhibitory activity lowers activity of primed circuits, allowing for recruitment of new circuits that may help to solve the problem. In the incubation period distributed sustained activity among primed circuits leads to various transient associations, most of them short-lived and immediately forgotten. Almost all of these activations do not have much sense and are transient configurations, fleeting thoughts that escape the mind without being noticed. This is usually called imagination. Interesting associations are noticed by the central executive and amplified by emotional filters that provides neurotransmitters increasing the plasticity of the circuits involved and forming new associations, pathways in the conceptual space.

In this view at the neural level creativity requires two components: 1) distributed chaotic (fluctuating) neural activity constrained by the strength of associations between subnetworks coding different concepts, responsible for imagination, and 2) filtering of interesting results, amplifying certain associations, discovering partial solutions that may be useful in view of the set goals. Filtering is based on priming expectations, forming associations, arousing emotions, and in case of linguistic competence on phonological and semantic density around words that are spontaneously created (density of similar active configurations representing words).

3.2. Insight

Some problems can only be solved with insight, a sudden Aha! experience that accompanies solutions of some problems [41]. Studies using functional MRI and EEG techniques contrasted insight with analytical problem solving that did not required insight [42]. An increased activity in the right hemisphere anterior superior temporal gyrus (RH-aSTG) has been observed during initial solving efforts and during insights. This area is probably involved in higher-level abstractions that can facilitate indirect associations. About 300 ms before insight a burst of gamma activity was observed. This has been interpreted by the authors as “making connections across distantly related information during comprehension ... that allow them to see connections that previously eluded them” [42]. Bowden *et al.* [43] performed a series of fMRI experiments, confirming these results. In their interpretation initial impasse is due to the inability of left hemisphere, focused on the problem, to make progress. This deadlock is removed when less-focused right hemisphere adds relevant information, allowing new associations to be formed. Aha! experience may result from activation by the pre-existing weak solution in the right hemisphere suddenly reaching consciousness when the activation of the left hemisphere is decreased.

An alternative interpretation of the involvement of the right hemisphere is based on the observation that connections between left and right hemisphere require long projections and cannot carry precise information. Therefore right hemisphere has only a global view at a higher level of abstraction, generalizing over similar concepts and their relations. This is also true for the left hemisphere, distributed activations in the right hemisphere form various configurations that activate back larger regions of the left hemisphere. Gamma high-activity burst projected to the left hemisphere will prime subnetworks with sufficient strength to form associative connections linking the problem statement with partial or final solution. Such solutions may initially be difficult to justify, until all intermediate steps will be categorized. The solution may be surprising, based on quite different idea than initially entertained. Gamma burst also activates emotions increasing plasticity of the cortex and facilitating the formation of new associations. One should expect that the same neural processes should also be involved in creative thinking, and that results of such processes will sometimes be assessed as creative.

3.3. Experiments with word associations

Relationships between creativity and associative memory processes have been discussed already in [44]. In experimental psychology investigation of priming effects is quite popular. The pairwise word association technique is perhaps the most direct way to analyze associations between subnetworks coding different concepts. These associations should differ depending on the type of priming (semantic or phonological), structure of the network coding concepts, the activity arousal due to the priming (the amount of energy pumped into the resonant system). In a series of experiments [45] phonological (distorted spelling) and semantic priming was applied, showing for a brief (200 ms) moment the priming cue (word) before the second word of the pair was displayed. Two groups of people, with high and low scores in creativity tests were participating in this experiment. Two type of associations were presented, close and remote, and two types of priming, positive (either phonological or semantic relation to the second word) and neutral (no relation).

Results of this experiments have puzzled the authors [45]. Creative people should have greater ability to associate words and should be more susceptible to priming. Less creative people may not be able to make remote associations at all, while creative people should show longer latency times before noticing such associations or claiming their absence. This is indeed observed. In addition neutral priming, based on the nonsensical or unrelated words, increased the number of claims that words are related, in case of less creative people stronger than positive priming, and in case of more creative people in a slightly lower way. Phonological priming with nonsensical sounds partially activates many words, adding intermediate active configurations that facilitate associations. If associations between close concepts are weak neutral priming may activate intermediate neural oscillators (pumping energy to the system, increasing blood supply), and that should help to establish links between paired words, while positive priming activates only the subnetwork close to the second word, but not the intermediate configurations. For creative people close associations are easy to notice and thus adding neutral or positive primes has similar small effect. Situation is quite different for remote associations. Adding neutral priming is not sufficient to facilitate connections in less creative brains when distal connection are completely absent, therefore neutral priming may only make them more confused. Adding some neural noise may increase the chance to form resonance state if weak connections exist in more creative brains – in the dynamical systems language this is called the stochastic resonance phenomenon [46]. On the other hand adding positive priming based on spelling activates only phonological representations close to that of the second word, therefore there is no influence. Priming on positive (related) meaning leads to much wider activation, facilitating associations.

These results support the idea that creativity relies on the associative memory, and in particular on the ability to link together distant concepts.

4. Creativity from computational perspective

Creativity is a product of ordinary neurocognitive processes and as such should be amenable to computational modeling. However, the lack of understanding what exactly is involved in creative activity is one of the main reasons for the low interest of the computational intelligence community in creative computing. Very few computational models addressing creativity have been implemented so far, the most interesting being Copycat, Metacat, and Magnificat models developed in Hofstadter's group [47]-[49]. These models define and explore "fluid concepts", that is concepts that are sufficiently flexible and context-sensitive to lead to automatic creative outcomes in challenging domains. Copycat architecture is based on an interplay between conceptual and perceptual activities. The first is implemented in a *Slipnet* spreading activation network, playing the role of the long-term memory, storing concepts, from simple objects to abstract relations. Links have length that reflect the strength of relationships between concepts, and change dynamically under the influence of the *Workspace* network, representing perceptual activity in the short-term or working memory.

Numerous software agents, randomly chosen from a larger population, operate in the Workspace, assembling and destroying structures on various levels. The Copycat architecture estimates "satisfaction" derived from the content of assembled structures and concepts. Relations (and therefore the meaning) of concepts and high-level perceptions emerge in this architecture as a result of a large numbers of parallel, low-level, non-deterministic elementary processes. This indeed may capture some fundamental processes of creative intelligence, although connections with real brain processes have not been explored [47]-[49].

Perhaps the simplest activity in which creativity is frequently manifested is in understanding and creating new words. In languages with rich morphological and phonological compositionality (such as Polish) novel words may appear in normal conversation (and much more frequently in poetry). Although these words are newly invented and cannot be found in any dictionary they may be understandable even without hearing them in a context. The simplest test for creative thinking in linguistic domain may be based on ingenuity of finding new words, names for products, web sites or companies that capture their characteristics. A test for creativity based on ingenuity in creating new words could measure the number of words each person has produced in a given time, and should correlate well with more demanding IQ tests.

Suppose that several keywords are given, or a short text containing such keywords, priming the brain at the phonetic and semantic level. The goal is to come up with novel and interesting words that capture associations with the keywords in the best possible way. Large number of transient resonant configurations of neural cell assemblies may be formed in each second, exploring the space of all possibilities that agree with internalized constraints on the phonological structure of words in a given language (phonotactics of the language). Very few of those imagined words are really interesting, but they all should sound correctly if phonological constraints are kept. A phonetically-detailed computational models of spoken word representation has not yet been created but experiments with simple statistical algorithm based on this idea gave quite interesting results [50]. Imagination is rather easy to achieve, taking keywords, finding their synonyms to increase the pool of words, breaking words into morphemes, syllables, and combining the fragments in all possible ways.

In the brain words that use larger subnetworks common to many words have higher chance to win competition, as they lead to stronger resonance states, with microcircuits that mutually support activity of each other. This probably explains the tendency to use the same word in many meanings, and create many variants of words around the same morphemes. Creative brains are probably supported by greater imagination, spreading activation to more words associated with initial keywords, and producing faster many combinations, but also selecting most interesting results through emotional and associative filtering. Emotional filtering is quite difficult to model, but in case of words two good filters may be proposed, based on phonological and semantic plausibility. Phonological filters are quite easy to construct using second and higher-order statistics for combination of phonemes (in practice even combination of letters is acceptable). Construction of phonological neighborhood density measure requires counting the number of words that sound similar to a target word. Semantic neighborhood density measures should evaluate the number of words that have similar meaning to a target word, including similarity to morphemes that the word may be decomposed to.

Starting from the following keywords: "portal, imagination, creativity, journey, discovery, travel, time, space, infinite", large number of interesting words has been generated, with about ¾ already used as company or domain names. This shows that the algorithm indeed creates new names in a similar way as human brains. For example, *creatival* is used by creatival.com, *creativery* is used by creativery.com. Some words have been used only a few times (at least according to the Google search engine), for example *discoverity* that can be derived from: disc, disco, discover, verity, discovery, creativity, verity, and may mean discovery of something true (*verity*). Another new interesting word is *digventure*, because it is easy to pronounce, and both *dig* and *venture* have many meanings and thus many associations, creating a subnetwork of activity in the brain that resonates for a long time.

5. Discussion and conclusions

Neurocognitive approach to higher cognitive functions presented here is obviously quite speculative, but it seems to be able to explain, at least qualitatively, many phenomena, such as creativity or automatization of skill learning, that were quite mysterious not so long time ago. Results discussed above support the idea that creative processes are based on ordinary cognitive processes and that understanding creativity and developing computational models of creativity may actually be easier to achieve than previously thought.

Creativity requires imagination and filtering. Imagination should be constrained by probabilities of composition of elementary operations, corresponding to activations of specific brain subnetworks. Products of imagination should be ranked and filtered in a domain-specific way. The same principles should apply to creativity in design, mathematics, and other domains, although in visual or abstract domain elementary operations and constraints on their compositions are not so easy to define as in the lexical domain. In arts emotional reactions and human reactions to beauty are rather difficult to formalize. Nevertheless it should be possible to create a network that learns individual preferences evaluating similarity to what has been evaluated as interesting. It is sufficient to observe how long and where a person looks in the art gallery to learn preferences and to create a new painting that would fit this person's taste. In abstract domains various measures of relevance or interestingness may be used for filtering, but to be interesting creative abstract designs (for example in mathematics) will require rich conceptual space, reflecting many neural configurations that may be potentially active.

Brain imaging and electrophysiological studies of brain activity during invention of new words, as well as during analysis of novel words read or heard, would make an interesting test of neurocognitive approach to creativity and may be done with methods already used to study word representations [6][7]. Probing associations and transition probabilities between brain states using experimental psychology techniques [44][45] should be easier with detailed models predicting the outcomes and explaining puzzling results that link associative memory and creativity [45]. Research program on creativity that includes neuroscience, cognitive psychology and theoretical modeling, focused on word representation and creation, could be an entry to a detailed understanding of this fascinating brain processes.

The ability to create new words may be tested quite quickly and it would be interesting to see how these tests correlate with more sophisticated and well established tests, and how words invented by humans compare with software-generated words. Computational models of creativity outlined in this paper may be implemented at a different level of neurobiological approximations, from detailed neural models to simple statistical approaches. Psychological theories are frequently based on conceptualizations that are difficult to justify as approximations to brain processes. Neurocognitive approach is well funded in neuroscience and may thus be directly tested using brain imaging, electrophysiological experiments and predictions of computational models. Creativity research is certainly on a good track.

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