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Brains and Education: Towards Neurocognitive Phenomics

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Abstract

Phenomics is concerned with detailed description of all aspects of organisms, from their physical foundations at genetic, molecular and cellular level, to behavioural and psychological traits. *Neuropsychiatric phenomics* tries to understand mental disease from such broad perspective. It is clear that learning sciences also need similar approach that should integrate efforts to understand cognitive processes from the perspective of the brain development, in temporal, spatial, psychological and social aspects. A new branch of science called *neurocognitive phenomics* is proposed, treating the brain as a substrate shaped by the genetic, epigenetic, cellular and environmental factors, in which learning processes due to the individual experiences, social contacts, education and culture take place. A brief review of selected aspects, from genes to learning styles, is presented, and a link between central, peripheral and motor processes in the brain linked to learning styles.

Keywords

Learning sciences, brain, phenomics, genotype, phenotype, memory, learning, cognition, learning styles.

INTRODUCTION

Successful learning requires formation of stable memory patterns that can be accessed by future brain processes. Brain substrate, the incredibly complex network of neurons, glia cells, genetic and epigenetic biochemical processes, maintains a delicate balance between stability and plasticity, the need to remember past experiences and the need to learn new ones. Full understanding of the biological learning processes requires explanations of processes on many levels of complexity, from genetic and molecular level to behavioral levels. The word *phenomics* has traditionally been concerned with the study of phenotypes, measureable traits of an organism. Rapid development of many branches of biology has broaden the phenomics perspective. In analogy to the concepts of *genome* and *proteom* that signify all genes and proteins *phenome* is the set of all phenotypes of cell, tissue, organs, or the whole species, expressed by their measureable traits. The *Human Phenome Project* (Freimer & Sabatti 2003) is gaining momentum, with plans to collect all kinds of information about phenotypes and linking it with genomic and any other available information that may be useful to understand many aspects of human behavior.

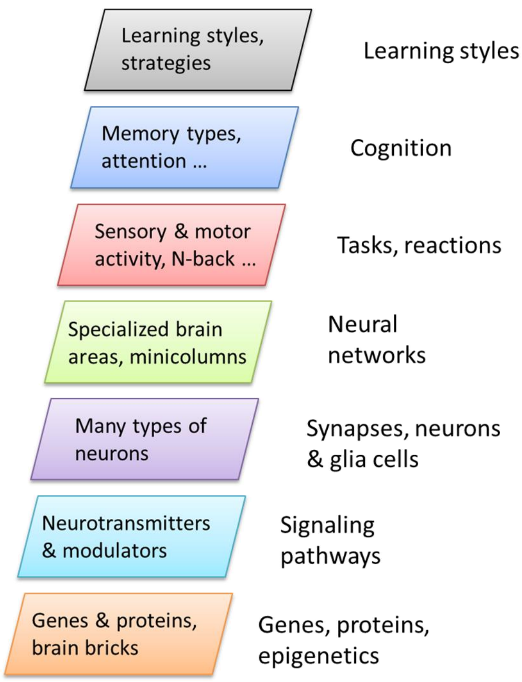
In 2008 the *Consortium for Neuropsychiatric Phenomics* (CNP) has been formed in the USA to focus on diagnostic and therapeutic methods in various mental disease, trying to understand biological mechanisms underlying phenotypes. Initial project will provide detail characteristics of groups of 300 people, each group suffering from Schizophrenia, Bipolar Disorder, and Attention-Deficit/Hyperactivity Disorder (ADHD), comparing genetics, brain structures, brain functions (memory, response inhibition) and behavior with 2000 healthy people. This project should help to understand how disruptions of normal functions influence phenotypes at each level (see http://www.phenomics.ucla.edu). This is obviously only the first step towards understanding of mental disease. Unravelling brain mechanisms and integrating information about the impact of environment on genetic and epigenetics mechanisms, formation of proteins, cellular systems and signalling pathways, development of neurons and neural systems, formation of cognitive phenotypes, manifestation of symptoms and syndromes in different contexts is a great challenge, but there is simply no alternative.

Comparable efforts in education do not exist yet. **Learning sciences** is an interdisciplinary field studying human learning, focused on psychological levels related to cognitive, social and cultural factors that influence learning process and help to design better learning environments. It is however clear that understanding learning and placing life-long education on solid scientific foundations requires comprehensive approach that should cover all aspects of phenomics. The problem is even more difficult than in case of neuropsychiatric phenomics, as the goal is not just repairing disrupted function but unfolding full human potential and improving quality of life. In this short article the idea of ***neurocognitive phenomics*** is proposed, a new direction in science that will take decades to complete. As in the case of neuropsychiatric phenomics, if the goal is to understand completely all processes that contribute to learning there is simply no alternative.

In the next section various levels of phenotype description are presented in relation to learning, and in the third section some remarks about possible use of this information at different stages of development, from pre-natal to the old age, is discussed. A brief discussion closes this paper.

FROM GENES TO LEARNING STYLES

Many branches of science contribute to understanding of developmental and behavioral processes. In Fig. 1 processes at seven levels of hierarchical description are presented. Any division of biological processes into such levels is a result of specific research approaches, different views that help to describe undivided reality. Genetics, neurophysiology, behavioral methods and psychology provide complementary descriptions of the learning processes that should be integrated into one comprehensive theory. Levels that are higher in the hierarchy have their own emergent properties that may not make much sense at the lower level. Information flows from genetic to behavioral levels and back, influencing processes at all stages and changing phenotypes. Psychiatry needs to identify distortions of this process while learning sciences should also be concerned with more subtle effects. The major factors that influence brain development include genetics, nutrition, infection, immune system responses to environment, experiences, influence of family and other people, and finally education.



Genes and Proteins

This is a world of incredible complexity. In a single cell more than half of its dry mass is due to proteins, and there are now more than 16 million known protein sequences, and about 85,000 full structures in the Protein Data Bank (PDB). At the molecular level basic building blocks of cells are constructed according to the master plan that is stored in the DNA. Millions of proteins are formed using information in RNA and DNA, constructing all cells, including neurons, in an environment that needs to supply many types of elements in sufficient quantities to ensure normal development. Serious intellectual deficiency (IQ less than 70) affects 1-3% of general population and has been linked to mutations in few thousand genes.

The execution of the DNA building plan is controlled by the environment through many types of epigenetic processes, altering gene expressions without changing the DNA sequence. Many types of epigenetic processes have been discovered and probably many more exist. DNA methylation (adding CH_3 molecules to predominantly cytosine bases) has been studied in relation to serious health conditions such as cancer for three decades. The *DNA Methylation Society* has even its own journal *Epigenetics*, covering medical, behavioral, psychological and nutritional epigenetic effects. Modification of chromatin (complex of DNA and proteins found in cell nucleus) may occur through methylation, microRNA or enzymes, and may silence one or both genes. This process, called in genetics *imprinting*, has also been implicated in many disease. Moreover, these changes may be inherited without modification of genetic sequence.

Development starts already in prenatal period. Many traits are inherited and shape the structure of the whole organism. In the womb basic traits, such as responsiveness and temperament, are determined to a large degree (Pesonen et al. 2008). The length of pregnancy may have strong influence on the development, cognitive abilities and tendency to acquire major disease. Epigenetic effects occur through all life but are strongest in the womb. Food intake, vitamins, drugs, alcohol, inflammation, viruses and bacteria causing disease, exposition to various pathogens in the environment are some of the factors that may influence epigenetic processes, leading to metabolic problems, blood defects and degeneration of internal organs, as well as more subtle influences on the brain. Phenotypes of identical twins who were raised in different conditions have shown different patterns in some muscle, lymphocyte and other tissues. This is an area of intensive research, focused around the *Human Epigenome Project* initiated in Europe in 2003. Although this project is oriented towards cancer and other serious disease implication in child development, neurological and psychiatric disease and aging has also been pointed out. Epigenetic processes differ in various tissues, so this project will be more complicated than the *Human Genome Project*. Epigenome may be affected in a simpler way than genome itself, therefore it should be an easier target to control. Immediate goal of this research is to prevent abnormal development, but long-term goal may be to ensure optimal conditions for development of the brain and the whole organism.

Signalling Pathways

Complexity of organisms is not directly related to the number of genes. Humans have probably less than 23,000 genes, similar number as the nematode worm, and about one quarter of the number of genes in wheat. What seems to be more important is the complexity of genetic regulation, epigenetic and posttranslational processes, and interactions among proteins. This interaction network, called *interactome*, in case of humans has been estimated to be about 650,000. It is several times larger than in simpler organisms (Stumpf et al. 2008). Proteins interact with other molecules creating functional complexes and networks of interactions that form metabolic pathways. Inside the cell they regulate concentration of biochemicals in different cell structures. Through various pores and channels in cell membranes substances are exchanged, bringing nutrients to the cell and allowing for communication with other cells. Some molecules that are part of membrane receptors are sensitive to the external environment, and they influence processes within the cell. The development and well-being of the organism critically depends on all signalling pathways.

Neural stem cells at different locations mature into different types of neurons and glia cells depending on the density of *neurotrophins*, glycoproteins such as reelin, extracellular matrix, retinoic acid (vitamin A metabolite), cerebrospinal fluid and the vascular environment. Many specific pathways that facilitate, inhibit or pattern neurogenesis have been discovered, but this is still largely unchartered territory.

Fundamental questions about cellular and molecular pathways need to be answered before therapies for neurodegenerative disease and control of these processes will be possible. In adult brains of mammals neurogenesis is limited to hippocampus and olfactory bulb areas. This helps to ensure stability of memory and behavior that has already been learned.

At present there is over 30 *"omics"* fields of study in the life sciences, inspired by genomics. Environmental factors that organisms are exposed to may cause disease in prenatal as well as postnatal stages of development. Research on the effects of such factors has been called *exposomics*. Investigation of nutritional aspects of bioactivity is called *foodomics*. So far attention is paid more to the dangers than to the possible benefits. Monitoring of environmental and nutrition effects on signalling pathways will contribute to prevention of developmental problems, reducing the number of children who need special education.

Neurons

The brain is not a general purpose computer. It is rather a multi-agent system, a highly specialized device that offers a large number of automatic responses, many of which can be adapted as a result of learning to realize complex cognitive functions. Cells in the brain – neurons and glia cells – are quite unique, they are the longest living cells in the body. Neurons come in a large variety, differing in size, morphology, length of axons and number of dendrites, dendritic spines, types of synapses and receptors. Some have very long axons providing links between distant brain areas (transversal connections, fascicle bundles, association fibres) helping to synchronize their activations, and connecting the brain with distant parts of the body through efferent and afferent nerve fibers. Others, including most interneurons, have short local connections, regulating the level of activation in the brain. A rough estimate of the number of different types of neurons is based on 1000 grey matter regions, each containing on average about 10 types of neurons, giving about 10000 types of neurons. Recent estimations of the number of neurons in the human brain (Lent et al. 2012) converge at 86±8 bln neurons in the whole brain, but only 16±2 bln in the cortex, less than 2 billion in the subcortical structures, the spine and other parts of the body, and about 69±7 bln in cerebellum, involved mostly in motor control and motor learning. This shows how important is precise movement control. Perception, memory and cognitive processes serve to enable action.

The development of neurons may go wrong in many ways caused by a large number of factors: the whole brain may develop in a wrong way at a gross anatomic level, genetic mutations, environmental and epigenetic factors may lead to misfolding of proteins damaging neural internal structures (mitochondria and other organelles), membranes, dendrites, spines, synapses. Neurotrophic factors that control proliferation and migration of neurons, neural apoptosis (programmed cell death) and synaptic pruning that should leave only useful functional connections between neurons may fail due to number of reasons. Neurons need to send spikes to stay alive, and may send bursts of no more than a few hundred spikes per second before they take a break and move into slow spiking mode.

Problems with development of neurons and their migration to proper places may lead to death of the fetus or to a serious neurodegenerative and psychiatric disease after birth. At present not much can be done about it. Many factors may be responsible for neural dysfunctions, therefore it is not surprising that in extensive studies of genomes of autistic people mutations in hundreds of genes have been weakly correlated with about 20% of autism cases (for the remaining 80% correlations are too weak to be statistically significant) and more than half of these mutations are also correlated with other mental disease. It is quite likely that serious mental disease such as autism or schizophrenia, and neurological disease such as epilepsy, result from subtle dysfunctions of neurons that make them incapable of forming proper networks. Such disease may have infinite number of variants, because the damage of different severity may occur in one or many types of neurons, in one or many brain areas, axons and dendrites may not branch correctly, brain circuits may be miswired, so each case of such disease may be unique.

Neural networks

Neurons are densely connected, with 1-2 bln synapses in one cubic millimeter of the neocortex. The total number of connections is of the order of 10^{14}, or 100 trillion, most of them between neurons in the neocortex. In the first and the second year of life several millions of new connections are formed every second! The total number of connections grows after birth reaching its peak around the third year of life, although the process of pruning and creating new connections continues for about 20 years, and is a bit different in the left and right hemisphere. Learning is largely based on specialization, efficient processing of information, specific associations that have to be established, and that requires better structural integration of brain networks. During adolescence density of gray matter still decreases, short-range connections are pruned and long-range myelination helps to synchronize distant brain areas. Repetition creates stronger pathways between neurons involved in representation of concepts that are learned, making associations more automatic. This is important in early perception, sharpening discrimination of sensory stimuli, seeing textures, contrasts and shapes, tactile sensations and auditory discrimination, filtering speech sounds that facilitate understanding language in a speaker-independent way. All sensory systems have to segment the incoming signals to enable invariant recognition. Brains of infants and babies develop these abilities in a spontaneous way in a proper environment without direct supervision or monitoring (Lamb et al. 2002). Positive effect of rich environments on formation of neural networks has been documented in animal research.

The complexity of the meso and micro-scale is overwhelming and cannot be precisely controlled by genetic processes. Neurons in the neocortex are organized in 6 layers and in cortical columns, with diameter of a fraction of millimeter. Each column contains a few tens of thousands of neurons of many types, forming densely connected vertical microcircuits, connected horizontally in a less dense way. The cortex is composed from a few millions of such minicolumns, and they serve as computational units with rich internal dynamics. At the macroscale brains have similar structures. It is surprising, but theoretical analysis shows that local microcircuits may have random connectivity and huge diversity to allow for more robust and efficient analysis of incoming spatiotemporal signals (Maass et al, 2002). “Small world” structure of brain networks, with important hubs where many connections converge, is also contributing to the efficient information processing.

System level

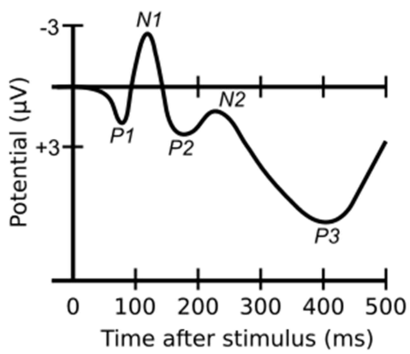
At the system level the whole brain is analyzed focusing on regions of interest (ROI), anatomically and functionally specialized brain areas. The *Human Connectome Project* started in the USA in 2009, mapping connectivity between about 1000 regions of interest to create “network map” for healthy adults and people with various mental problems. This project gained popularity and has been followed by plans to make connectomes at more detailed the mesoscopic and microscopic levels, and even extended to the prenatal period and early infancy (*Developing Human Connectome Project*, UK 2013). This top-down description of how brains process information has already shown that brains of people suffering from Alzheimer's disease, autism and schizophrenia differ from healthy brains.

There is no simple brain structure-single function correspondence. Each region may contribute to many functions and at the same time each function may be realized engaging different subsets of regions (Anderson, 2010), so only a partial localization of functions is possible. There are significant individual differences in the way brains processes information, and they certainly influence learning style of individuals. Such differences are relatively subtle comparing to the changes observed in brains of people with serious mental problems. Pharmacological interventions target large subsystems that use the same type of signaling pathways based on neurotransmitters and their receptors, for example influencing the level of serotonin or dopamine. Such interventions are very coarse, changing dynamics of the whole brain. Some neurotransmitters are produced locally in neurons spread around the brain but most are transported from the nuclei that are in the brain stem, including serotonin (raphe nuclei), norepinephrine (locus ceruleus), or dopamine (ventral tegmentum area and substantia nigra in midbrain). Brain stem is responsible for many automatic responses, homeostasis, selection of the global behavioral state, activating and inhibiting large brain areas depending on the context, with more precise selection of actions done by big subcortical nuclei called basal ganglia. Reward information is used to choose, learn, prepare and execute goal-directed behavior, mediated by dopamine neurotransmitters, engaging medial temporal cortex involved in the detection and prediction of rewards, and orbitofrontal cortex and amygdala that evaluate relative reward values and expectations (Berns, 2005; Gottfried, O'Doherty & Dolan, 2003; Schultz, 2000). The overall level of arousal and awareness is determined by the reticular formation in the brain stem.

Representation of goals is maintained in parietal, premotor and dorsolateral prefrontal cortex (Berns, 2005). 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 (Duff, et al. 2005). Short-term memory is based on arousal of subsets of neurons that change the flow of neural activation, therefore it has very limited capacity, but activation traces may prime the activity and decisions long after the active memory has changed. Holding several things in memory and being able to store and quickly return to previous thoughts is very important for problem solving, including understanding of complex sentences and situations. The more parallel plans the brain is able to pursue the better. Prefrontal cortex is the seat of such working memory with capacity for only 3-4 visual objects (Baddeley, 2002), and about 4-9 chunks of simpler information, such as digits or simple symbols (Cowan, 2005). A distinct verbal working memory system is used by the brain to analyze the syntactic structure of a sentence and determining its meaning (Caplan & Waters, 1999). Higher capacity of the working memory is strongly correlated with intelligence.

Cognition level

At the cognition level mental processes that can be observed using behavioral tests are investigated. These processes are described in psychological and information processing terms and have only recently been partially linked to the brain processes. Many cognitive functions involving perception and motor control have now neural network models that can be verified using computational simulations and neuroimaging. Deficits in quantization of basic speech sounds (phonemes) lead to phonological dyslexia and learning problems at school. The brain that has rich neural structure,



with many synaptic connections may easily adapt to the complex challenges posed by the environment. The density of synaptic connections may be inferred from the sensory event-related potentials (ERPs), for example auditory cortex reaction to simple repetitive stimuli (speech or general sounds), measured by averaging EEG signals from the temporal brain areas. This signal shows an echo of the brain processing sensory information, and thus reflects connectivity and changes taking place in the developing brain. The first major components of the ERPs are negative peak that appears 100 ms (N100), followed by a positive peak 200 ms after the stimulus in adult brains. Typical N100-P200 complex develops only after 10 years of age. Initially in the first four years the first component is positive (P1 in Fig. here).

Reading and development of language-related abilities requires precise recognition of phonemes, recognition of graphical symbols (graphemes, logograms), linking this information to form chains of active local brain regions, activating premotor cortex to produce appropriate sounds. Speech input synchronizes activity in the temporal and frontal cortex (premotor, Broca area) forming unique patterns of activation for ordered strings of phonemes, leading to the active subnetworks (resonant states) representing word forms (Grossberg, 2003). Analysis of the N200 feature of event-related potentials shows that phonological processing precedes activations that spread all over the brain by about 90 ms (Pulvermueller, 2003). These extended activations allow for associations and interpretation of the word in a given context, binding phonological representations of symbols with related perceptions and actions, grounding the meaning of the word in a perception/action network. Symbols in the brain can therefore be seen as labels for prototype activations including how they sound like (auditory cortex), how they are pronounced (premotor cortex), what visual, tactile, olfactory, gustatory, emotional and motor associations they have. Such encoding provides easy access to associations, phonological as well as semantic similarities between concepts.

Differences between cognitive abilities may be inferred from event-related auditory potentials immediately after birth. Tests done with reaction to the groups of syllables: bi, di, gi; bae, dae, gae; bu, du, gu; ba, ga, da, performed in the first days of life show that the structure of ERPs (differences in reactions to similar sounds) allows for prediction of emergence of reading disorders 8 years later (Molfese 2008; Molfese et al. 2002). The speed of brain reaction of infants that will have problems in later life is about 200 ms slower. The differences in word recognition of 8-years old reaches 500 ms, and the recognition is not stable, leading to problems in reading and text comprehension. In longitudinal study Fagan et al. (2009) investigating visual recognition memory (using tests of selective attention to novelty) in babies 6-12 month old found strong correlation with IQ tests when these babies became young adults. These and many other results are in agreement with the idea that prenatal and infant periods are critical in development of brains that facilitate intelligence. Research performed on rats showed that environmental enrichment in early life stages leads to many positive effects, including thicker cerebral cortices, 25% increase of synaptic density and 12-14% increase of glia cells. This increase seems to stay for a longer time even when rats are moved to impoverished environment (Simpson & Kelly, 2011). We have not yet learned how to stimulate babies to boost their development at a very early stage, but this is exactly what we plan to do in the near future.

Segmentation of experience seems to be operating at all levels (Zacks et al. 2010). Practical conclusion for teaching is that all material should be given in appropriate chunks, trying to create as many associations with what is already known as possible. Meanings are stored as activations of associative subnetworks. Different patterns of its activation may be distinguished and processed 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 (Grossberg, 2000; Grossberg, 2003).

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 precise meaning of a concept is always modified by the context, so explanation of the meaning in a thesaurus can only be approximate. Overlapping patterns of brain activations for subnetworks coding word representations facilitate strong transition probabilities between concepts, activating semantic and phonological associations that easily “come to mind”.

Another aspect of brain function important for intelligence and creativity is synchronization and speed. Myelination of long axons (white matter) helps groups of neurons to synchronize and process information (Singer 1999). The speed of thinking and creation of spontaneous thoughts or images depends on synchronization of distant brain areas. Creativity is one of the most mysterious aspects of the human mind (Duch, 2007, 2007a). Creative brains have trained neural network, encoding dense potentially accessible states and enabling rich association between them. Spontaneous processes arising from blind variations activate various patterns depending on the context that is used for priming. Selective filtering of interesting patterns is based on associations and emotions. This is in agreement with fairly old *Blind Variation Selective Retention* psychological model of Campbell, recently reviewed by Simonton (2010), and presented in computational framework by Duch and Pilichowski (2007).

Learning, forming any kind of memory, requires physical changes in the brain, or neuroplasticity. This is enabled by various processes at the molecular level that make the synapses stronger or weaker. Although pharmacological interventions may influence some of these processes and may be quite useful in case of memory problems there is a balance between associations needed for creativity, and good memory that strongly binds the thought and decreases creativity. It would be ideal to be able to increase temporarily the window of neuroplasticity and after introducing the information that should be learned to decrease it again. In a way this is what emotions do, realizing neurotransmitters and neuromodulators that increase neuroplasticity. Another possibility is direct activation of the brain using transcranial magnetic stimulation (TMS), or direct current stimulation (DCS). There are indications that such stimulation may accelerate the speed of learning and facilitate creativity (Chi & Snyder, 2011).

Learning styles

The idea that people have different learning styles became very popular in education after the publication of David Kolb book (1984), and his *Learning Styles Inventory* scheme. He analyzed learning processes along two dimensions: preferred mode of perception – from concrete to abstract – and preferred mode of action – from individual experimentation to reflective observation (Pashler et al. 2008). This division led to 4 extreme types of learners: divergers (concrete, reflective), assimilators (abstract, reflective), convergers (abstract, active), and accommodators (concrete, active). The *Learning Styles Inventory* is a tool used to determine individual style, and is distributed commercially. Some neuropsychologists could not see relations of these ideas to the neuroscience and therefore have criticized learning styles as baseless. However, it seems that it can be related to the brain processes in a rather simple way. Let’s distinguish 3 types of brain activity:

1) sensory level S, with strong synchronization of groups of neurons that are involved in processing auditory, visual and other sensory information (mostly occipital, superior temporal and somatosensory cortex);
2) central level C, with abstract concepts that have no sensory components and thus engage neurons in association cortices only (mostly parietal, temporal and prefrontal lobes), and

3) motor cortex M that involves activations of motor imagery and physical action (mostly frontal cortex and basal ganglia).

The first dimension proposed by Kolb may be linked to the dominance of sensory processes, coupling S⇔S activations, with weaker coupling between abstract central processes C⇔C. Strong top-down links between association cortex and visual and auditory cortices will lead to vivid imagery dominated by sensory experience. In extreme cases this is present in autistic people, who have very vivid and detailed imagery, but little abilities to generalize experience or relate it on a more abstract level to general knowledge. Attention results from synchronization of groups of neurons and in the case of autistic people synchronization is limited to sensory cortices, making the shifts of attention from perception that binds their brains quite difficult, as it has been demonstrated in numerous experiments. In case of people with Asperger syndrome, a milder version of autism, the lack of understanding of metaphoric language indicates that reference to physical objects also activates sensory cortices strongly, although perception does not constrain brain activity so strongly as in the cases of autism.

If the top-down links are weak the central C⇔C processes will dominate, no vivid imagery should follow thoughts, but abstract thinking may be more efficient. This type of thinking may characterize mathematicians, logicians, theoretical physicist, theologians and philosophers who prefer to think about abstract ideas. Stronger bottom-up links S=>C will activate association cortex without strong activity at the S⇔S level, leading to abstract thoughts.

The second dimension, passive-active is linked to the synchronization between motor and central processes M⇔C, and sensory-motor processes M⇔S. Brain dynamics of autistic people may also be dominated by processes at the motor level M⇔M, with repetitive movement or echolalia. Assimilators are probably people with weak connections from S=>M and C=>M, but strong C⇔C activity, therefore they are prone to abstract conceptualization, reflective observation and inductive reasoning. Strong C=>M and C⇔C flow of activity leads to converger style, combining abstract conceptualization, active experimentation, using deductive reasoning in problem solving. Divergers are dominated by concrete experience S⇔S and have also strong C⇔S connections, facilitating reflective observation, but weak connections to motor areas. They have strong imagery but also create novel ideas. Accommodators have balanced sensory, motor and central processes and thus combine concrete experience with active experimentation supported by central processes S⇔C⇔M.

An objective tests of the learning style based on brain activity may thus be possible. Unfortunately connectome data do not tell us much about direction of the connections, but this may be inferred using EEG techniques.

As with many other processes, like perception of ambiguous figures, memory recall, planning, problem solving, spontaneous creative activity requires 3 steps:

- Preparation of the brain and conscious introduction of the problem.
- Unconscious associations that add new facets providing steps towards solution.
- Conscious recognition of most interesting associations.

Learning requires trained brain network that is primed by the description of the problem. This provides a kind of space for ideas, where new activation patterns and associations are implanted. If the basic concepts have not been learned properly the brain network will not be able to create useful associations. If too many processes in the brain are active priming will not be effective. There is a tradeoff between rigid automatic responses and the ability to make novel associations. Insight processes and involvement of the right hemisphere have been experimentally investigated (Jung-Beeman et al. 2004; Bowden et al. 2005) and interpreted by Duch (2007).

The information that needs to be analyzed must first appear 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.

Stating the problem by reading, listening or thinking about it puts it into working memory, that is activates (primes) a subset of long-term memory patterns and thanks to sustained attention binds them together. 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 (Baars, 1988). New activation patterns are recognized by the central executive as useful steps towards solution, thus changing the current state of the problem; this cycle is repeated until a solution is found or an impasse is reached. Final solution is a series of associations that lead from the initial brain state – problem statement – to the final state, representing problem solution.

This view leads to unified approach that should be the basis of learning: prepare the brain, introduce the problem, wait for the solution. This process may be done effortlessly but requires ability to focus and to prepare the brain for learning. Preparation of the brain may be done using mental relaxation response techniques (Benson, 2001), or physical exercises that require focusing on bodily sensations. The use of neurofeedback techniques has also been quite successful (Gruzelier, 2009). However, memorizing basic facts needs to be done first to create necessary basis for the space of concepts that is necessary for solving problems in a given domain. The *Core Knowledge Foundation* tries to teach such basic concepts that should be useful to everyone, starting from preschools, with programs in mathematics, number sense, and orientation in time and space.

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 (Duch 2005, 2007).

SUMMARY AND CONCLUSIONS

An overview of various factors that contribute to learning has been presented, with a new analysis of learning styles linking it to the peripheral (sensory), central and motor brain processes. Most programs related to genetics, epigenetics, signal pathways, neurons and their networks are at present aimed at serious mental disease rather than understanding and improving learning. It is clear that we are at the beginning of a long way towards neurocognitive phenomics that will take a long time and will require a lot of effort to develop. It is a big step beyond learning styles. Analysis presented here is at some points rather speculative, but it seems to be able to explain, at least qualitatively, many phenomena, linking cognitive psychological level, and learning styles educational level, with brain processes.

Many important ideas related to education, such as the role of emotions, training of motivation, exploration, strong will, depletion of willpower, goals setting, have not even been mentioned, although they are very important. Many ideas that education has been experimenting with are accommodated in a natural way in neurocognitive phenomics. Understanding brain processes explains some aspects of learning, creativity, automatization of skills, insight and many other processes that were quite mysterious not so long time ago. This view opens many possibilities for technological support of development of full human potential, starting from the prenatal period and the infancy.

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Biography

Włodzisław (Wlodek) Duch started his scientific career from theoretical physics, then moved computational intelligence (CI) methods developing meta-learning schemes that automatically discover the best model for a given data and is working now on development of neurocognitive informatics, algorithms inspired by cognitive functions, information flow in the brain, learning and neuroplasticity, understanding attention deficit disorders in autism and other diseases, infant learning, toys that facilitate mental development, creativity, intuition, insight and mental imagery. He worked as a Visiting Professor in Germany, Japan, Singapore and USA, and currently serves as the Vice-Rector for Research and ICT Infrastructure at Nicolaus Copernicus University in Toruń. Search for “W. Duch” to see his full CV.