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AN UNIFYING NEURONAL MODEL FOR NORMAL AND ABNORMAL THINKING

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Abstract - Since little is still known about fundamental brain mechanisms associated to thought, its different manifestations are usually classified in an oversimplified way into normal and abnormal, like delusional and disorganized thought or creative thinking. Considering dopaminergic signal-to-noise neuronal modulation in the central nervous system, and the existence of semantic maps in the human brain, we developed a self-organizing neural network model to unify different thought processes into a single neurocomputational substrate. We performed simulations varying dopaminergic modulation and observed the total patterns that emerged at the resulting semantic map, assuming that these correspond to thought. The model thus shows how normal and abnormal thinking are generated, and that there are no clear borders between their different manifestations. Actually, a continuum of different qualitative reasoning, ranging from delusion to disorganized thought, and passing through normal and creative thinking, seems to be more plausible.

Keywords: Creativity, Delusions, Disorganized thought, Cortical maps, Dopaminergic modulation, Neural network models.

1. Creativity

One of the most interesting and fuzzy of our mental activities is referred to as creativity. Since Classical Antiquity, the act of creating new ideas, original artistic expressions, and unforeseen machinery has fascinated the philosopher and the layman. The mystery of creation seems to come from the fact that the "new" emerges from the "nowhere" of old, well-known, and current concepts.

Many have tried to define and partially explain the creative phenomenon. For Gagné, it could be the combination of ideas from different and largely separate knowledge fields (Novaes, 1971), or almost equivalently, according to Rogers, the ability of making unusual relationships or unexpected connections between elements (Rogers, 1949). Associationists say that creative people are capable of linking external stimuli to highly unlikely answers, generating solutions masked for the majority (Franchi, 1972). Cognitivists explain creativity as another form of information processing or cognitive style (Franchi, 1972).

Focusing attention on the central elements of a problem and disregarding the peripheral ones is a good strategy for finding a conventional and unique solution to a problem. This convergent-thought approach is naturally taught at schools and societies and used by most people in everyday life situations. However, broadening attention to a wider range of elements and regarding them as potentially relevant may be a better approach to finding new and creative solutions. This divergent thought style follows many directions in parallel and allows the discovery of unusual associations of ideas.

For the Gestalt School, creativity is the reorganization of mental structures, producing new associations of ideas depending on the perception of the real situation (Wertheimer, 1968). The more flexible the mental reorganization, the more creative the thinking process. This is similar to the associationist description mentioned above.

Psychodynamical theories were also proposed to explain creativity. Freud (Freud, 1907) suggested that the creative act is a consequence of a fantastic view of the world, when reality frustrates a subject's desires. As in childplay or dreaming,

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these acts allow a substitute satisfaction for certain desires repressed by the superego. The manifestations of these creative acts are thus referred to as sublimation. According to psychoanalytic theory, if incursion to fantasy does not alleviate excessive frustration, the subject may develop neurotic or psychotic symptoms, which are pathological disguises for infantile fantasies (Freud, 1917, Franchi, 1972). In the model of Adaptative Regression (Kris, 1952), the creative process is viewed as a regression to unconscious levels, which allows a momentary freedom from stereotyped and conventional scenes. Psychosis is seen as an involuntary and uncontrolled regression to childlike modes of thinking, while the creative person is capable of a temporary and controlled regressive trip.

Although inconclusive (Schachtel, 1959, Maslow, 1962, Coleman, 1960, Rogers, 1949, Hebeisen, 1960), psychodynamical theories gather in a single model creativity, psychopathology and unconsciousness. Indeed, many reports express a strong correlation between creative and psychotic thinking. In the seventies, creative writers and maniacs were compared and a common tendency to broaden or shift conceptual boundaries (overinclusion) was observed (Andreasen, 1976). The overinclusiveness of the maniacs was based on bizarre associations, while that of the writers was due to the recognition of original and valuable associations. In another study, schizophrenics and creative adults were tested and a common wider attentional focus was noted along with a capacity of making looser associations (Dykes, 1976).

In the eighties, creativity and schizophrenic thought were suggested to be related to the same cognitive process, based on the Alternate Uses Tests (Keefe, 1980). Recently, almost three hundred famous biographies were rated by the DSM III and creativity was again linked to pathological personality characteristics or disorders, mainly bipolar disorder (Post, 1994). Another study concluded that coarse rather than focused semantic activation is strongly related to schizophrenic thought and creative thinking (Leonhard, 1998). Whatever the relation between psychopathology and creativity is, they seem to have some common aspects, like the idea of broader, distant or looser association making and unfocusing of attention. In the present paper, we explore these commonalities to define an unifying model for creative and disturbed thought.

2. Delusions and Disorganized Thought

As described by Karl Jaspers (Jaspers, 1966), delusions are thought processes that deviate from normal logical thinking by producing false judgements with a pathological origin. These processes manifest themselves by ideas with characteristics such as subjective certainty, incorrigibility, and impossibility of content. The delusion is a primary phenomenon that expresses itself through judgments, and is not to be regarded as the judgment itself. For this reason, delusions cannot be understood and corrected even in the presence of many logical arguments. This classical characterisation of delusional symptoms has been reviewed, since for example, some delusions are indeed possibly true and many of these characteristics can be applied to religious convictions (Janzarik, 1988). Impossible, improbable, or even true, a delusion is a statement made in an inappropriate context or without a logical justification. Normal thought has reasons to justify itself and can embed the possibilities of doubt. Delusions are not followed by adequate and reasonable justifications and their property of total and unquestionable certainty leads to their incorrigibility.

Delusional manifestations may be of three types: delusional perception, representation and cognition. In the process of delusional perception, the patient attaches an abnormal meaning to a sensation or perception of the world. Usually, the real world perception is taken as a signal or revelation to the patient. In the delusional representation, a memory trace returns to consciousness with a new meaning, while in the delusional cognition there are no perception or memory traces to attach to new interpretations, only an intuition that suddenly appears.

For Freud, a delusion is a defence process where judgment mistakes are made when the ego tries to isolate from consciousness intolerable representations. When an intolerable idea is inseparably connected to reality, the only way of isolating it from consciousness is to detach from reality (Muller, 1976). The main fundamental defense mechanism involved in the production of delusional ideas is referred to as projection in psychoanalytic theory. In projection, mental elements undesirable to consciousness are wrongly attributed to the external world. For example, in the famous case history of Schreber studied by Freud (Freud, 1911), the persecutive delusion should have its origin in the following projection: the repressed homossexual desire expressed by the idea *"I (a man) love you (another man)"* is transformed into *"I do not love you, I hate you"* and, since hate is also to be condemned, the subject makes the projection, *"he hates me and persecutes me"*.

For the Gestalt School, some neurophysiological process breaks the coherence between perception and thinking, leading to the emergence of new "gestalts" (Muller, 1976). Following the ideas of Hebb about cell assemblies (Hebb, 1949), Fish developed a neurobiological theory (Fish, 1973) where the overstimulation of the cell assemblies that represent ideas of a sequential thought would lead to the process of delusion. In his theory, the reticular formation was the center responsible for the referred overstimulation, and the neurotransmitter serotonine was the neurochemical basis for the delusional thinking. Another important theory that relates delusions to the neurotransmitter dompamine will be reviewed in the next section.

Delusions are stimulated by a mixture of anxiety, hiperarousal, suspicion, and the attachment of meaning to insignificant events. Once a meaning is attached, the patient will not question the event anymore and will further elaborate on it. This delusional work is an attempt to find coherence in his unusual thoughts. Acute delusions respond to neuroleptic treatment, while chronic delusions tend to be resistant. Chronic delusions are not a momentary state of the person, but part of the individual´s values, intentions, and views. It seems that the chronically deluded patient has a structural deformation, that may have developed from the dynamical forces present in the acute delusion (Spitzer, 1995). Chronic delusions may also develop from a state of sensorial deprivation, for example, such as that which occurs with isolated individuals (prisoners, refugees, hearing loss).

Disorganized thought is characterized by a loss of the capacity to associate ideas in a logical way. Ideas completely heterogeneous to each other are associated, so that the subject´s discourse becomes incoherent, and many times uninteligible. This phenomenon is observed specially in schizophrenia, but also in delirium and in excited maniac patients. In schizophrenia, disorganized thought, along with delusions and hallucinations, is considered a positive psychotic symptom, and responds well to neuroleptic treatment.

3. Dopaminergic Modulation

The catecholamines norepinephrine, epinephrine, and dopamine are important neuroactive substances produced in some brain sites and released at distant and widespread areas in a diffuse or divergent way (Molinoff, 1971). These substances do not act through membrane ion channels but, instead, activate intracellular messengers, promoting a longer effect than the other neurochemicals released by synapses inside the brain. Since these other chemicals have specific and local synaptic patterns, act through ion channels, and have short-lasting effects, it is interesting to suppose that they differ from the catecolamines in function. Indeed, the substances released by synapses in the CNS may be classified into the two broad categories of neurotransmitters and neuromodulators (Servan-Schreiber, 1990). Due to the fast action and connection patterns of their producing synapses, neurotransmitters seem to be involved in the immediate processing of signals, while the neuromodulators, with their opposing properties, suggest a regulatory function, modulating the operational characteristics of the receptor neurons, i.e. their responses to neurotransmitters (More, 1978).

Increases or decreases in the catecholaminergic levels have behavioral consequences in arousal, attention, learning, memory, and motor responses (Spitzer, 1997). It is still not clearly verified, but it seems plausible to assume that catecholamines affect the neuronal ability to discern what is information from what is noise in a signal. Some authors suggest that these neuromodulators enhance the stronger signal and dampen the weak one (Spitzer, 1995), while others advocate that they enhance the cell sensitivity to either excitatory or inhibitory signals (Servan-Schreiber, 1990). Whatever the mechanism is, the net effect is the enhancement of the signal in relation to the background, spontaneous activity called “noise.” The signal-to-noise ratio at neuronal level has been associated with the performance in some cognitive tasks and behaviors, including the deviant behavior of psychosis.

The dopamine hypothesis of schizophrenia advocates that the disorder is caused by an overactivity of the brain dopaminergic system (Spitzer, 1995). Observations that dopamine antagonists alleviate schizophrenic acute symptoms support the hypothesis (Davis, 1991). An elaboration of this hypothesis is that the dopamine release is chronically reduced in schizophrenic patients, leading to the upregulation of the postsynaptic receptors and a consequent intensified response in moments of normal or increased dopamine release, for example, due to environmental stressors (Grace, 1991). This would explain both, the positive and the negative, symptoms of the disease.

A relation between acute delusions and dopamine activity is clear from the fact that amphetamine can cause psychotic states with paranoia, hyperarousal, hyperactivity, and suspiciousness. It also seems that a decreased dopamine level leads to a lower signal-to-noise ratio and looser associations of thought, allowing the creation of new relations (Spitzer, 1995). For example, overinclusion and semantic priming are two phenomena observed in schizophrenic patients, that can be related to lower dopamine levels and to abnormally looser thought associations (Spitzer, 1997).

4. Cortical Maps

In the middle of the 19th century, Helmholtz and Mach studied many phenomena related to visual perception in humans. Particularly, they were interested in optical illusions, like the fact that edges or contours between light and dark parts of an image tended to be enhanced in relation to the light and dark interior of the image. They explained the illusion, hypothesizing that in the human retina the cells are excited by light that converges to a central region and are inhibited by the light that projects to the surrounding areas. Almost a century later, experimental results showed that the eye of the crab called *Limulus* (Hartline, 1957) and some vertebrates (Kuffler, 1953) have a structure, then called on-center/off-surround, in which a neuron is in cooperation, through excitatory synapses, with the neurons in the immediate neighborhood while it is in competition with the neurons which lay outside these surroundings. There is experimental evidence supporting that the same mechanism is also present in the mammalian central and peripheral nervous system. It seems that pyramidal cortical cells are connected in this on-center/off-surround way (Szentagothai, 1967). Other areas in the brain, like the hippocampus and the cerebellum show the referred hardwired structure (Andersen, 1969 , Eccles, 1967).

Competition and cooperation are found not only statically hardwired, but also as part of many neuronal dynamical processes. As a matter of fact, competition is essential to neurodevelopment where neurons compete for certain chemicals. In synaptogenesis, for example, substances generically called *neural growth factors* are released by stimulated neurons and, spreading through diffusion, reach the neighboring cells, promoting synaptic growth. Cells that receive neural growth factors make synapses and live, while cells that have no contact with these substances die (Kandel, 1991). A neuron that releases neural growth factor guides the process of synaptic formation in its tridimensional neighborhood, becoming a center of synaptic convergence. When some neighboring neurons release different neural growth factors in different amounts, many synaptic convergence centers are generated and a competition is established between them through the synapses of their surroundings. It seems that at least two processes participate in the dynamics of synaptic formation: pre-synaptic neurons competing for neural growth factors to survive, and post-synaptic neurons that release neural growth factors competing for synapses that will keep them alive with stimuli. It is worth noting that, since a single neuron is capable of receiving and releasing neural growth factors at the same time, the two competing processes described above effectively occur in every neuron and, consequently, a signaling network is established to control the development and plasticity of neuronal circuits. Remembering that all this competition is started and controlled by environmental stimulation, it is possible to have an idea of the way the environment records or represents itself in the brain.

The competition processes described above are essential to the formation of some neuronal organizations called *maps*. A neural map is a biological circuit composed of two sets of neurons, called domain and image, in such a way that similar patterns of activation of the domain are projected to neighboring neurons in the image. In other words, a neural map is a projection that transfers similarities in the domain to spatial relationships at the image. Maps were first observed in 1937 (Penfield, 1937) and later the concept was refined (Penfield, 1950), taking the somatosensory and motor cortices as models. Studies of the visual (Hubel, 1965), somatosensory (Mountcastle, 1957), and associative (Goldman-Rakic, 1984) cortices showed that small regions of those tissues respond to similar stimuli. Indeed, it is possible to represent stimuli associated to characteristics such as position, orientation, color, spatial frequency, auditory frequency, and also meanings (Robson, 1975, Reale, 1980, Ritter, 1989, Spitzer, 1995) in neuronal circuits as maps.

These maps are subject to constant change, not only in the neurodevelopmental phase, but throughout life as a function of the subject´s experiences (Mezernich, 1993). Monkeys trained to discriminate between two different vibrations imposed to the finger skin showed an increase in the region of the somatosensory cortex responsible for the finger representation (Recanzone, 1992). Marked cortical changes were also found in blind subjects, when comparing the braille reading finger cortical representation to the other fingers´ representations (Pascual-Leone, 1993).

Maps have puzzled neuroscientists in the last decades, mainly the question of how they arise from the simple on-center/off-surround wiring pattern. Computational theories gave some important insights to the problem, since some cortical maps are artificially developed from simple governing rules for synaptic plasticity in computer simulation models. The most general of these models is called the *Self-Organizing Map* (Kohonen, 1982), in which two sheets of neuronal tissue with $\boldsymbol{n}$ neurons each, corresponding to the domain and the image, are initially randomly connected in a way that every neuron $\boldsymbol{i}$ at the image receives synaptic projections $\boldsymbol{w_i \in R^n}$ from every neuron at the domain (see Figure 1). Neurons at the domain don't form synapses among themselves and receive "sensory" inputs (stimuli), while neurons at the image make synapses following the on-center/off-surround paradigm, i.e., short-range excitation or cooperation and long-range inhibition or competition (see Figure 2).

The model neuron is simply represented by the sum of all the input stimuli weighted by the synaptic strengths that bring them. The excitation or inhibition of the model neuron is decided in relation to a threshold value θ. If the sum of stimuli is greater than this threshold, the neuron is said to be excited. Otherwise, it is assumed that it is inhibited.

The on-center/off-surround synapses don't change during the development of the map, while the synapses between the domain and the image are modified along the process of map formation. Indeed, every time the neural network is in contact with a stimulus $\boldsymbol{x_k \in R^n, k=1,2,...}$ in its domain, there will be only one excited neuron $\boldsymbol{i^*}$ at the image because the short-range cooperation and long-range competition makes the more excited neuron inhibit the others. The position $\boldsymbol{r^*}$ of this winner neuron at the image determines how much the synapses will be modified. Synapses from neurons closer to the winner will be strongly changed, in such a way that these neurons will be more intensely excited by the stimulus $\boldsymbol{x_k}$ in the future. Synapses from neurons distant from the winner will be weakly changed or not changed at all, depending on the dispersion $\boldsymbol{\sigma}$ of the neighborhood function $\boldsymbol{\phi(r_i, r^*)}$, where $\boldsymbol{r_i \in R^n}$ gives the position of a neuron $\boldsymbol{i}$ at the image sheet. By this process, every neuron in the image will be more easily excited by the stimulus $\boldsymbol{x_k}$ (synaptic facilitation) in the future. The development of the map is a consequence of the fact that the amount of synaptic facilitation is a function of the distance from the winner neuron. The process of synaptic modification $\boldsymbol{\Delta w_i^l}$ for each neuron $\boldsymbol{i}$ is repeated for every learning step $\boldsymbol{l}$, where the stimulus $\boldsymbol{x_k \in R^n}$, $\boldsymbol{k=1,2,...}$ is presented to the neural network, and is given by

$$\Delta w_i^l = \rho(l)\,.\,\phi(r_i, r^*).\,(x_k - w_i), \qquad (1)$$

where $\boldsymbol{\rho(l)}$ is the learning rate defined by

$$\rho(l) = \rho_0 . \beta^{(l-1)}; \; 0 < \beta < 1, \; l = 1, 2 \quad ,(2)$$

The learning rate begins with the value ρ_0 and decreases at each learning step l with a rate β. The neighborhood symmetric function $\phi(r_i, r^*)$ takes the form of a gaussian function (Figure 3)

$$\phi(r_i, r^*) = exp -(\| r_i - r^* \|^2 / 2 \; \sigma(l)^2), \quad (3)$$

where the dispersion $\sigma(l)$ at each learning step is given by

$$\sigma(l) = \sigma_0 . \alpha^{(l-1)}; \; 0 < \alpha < 1, \; l = 1, 2 \quad (4)$$

and α is a decrement rate.

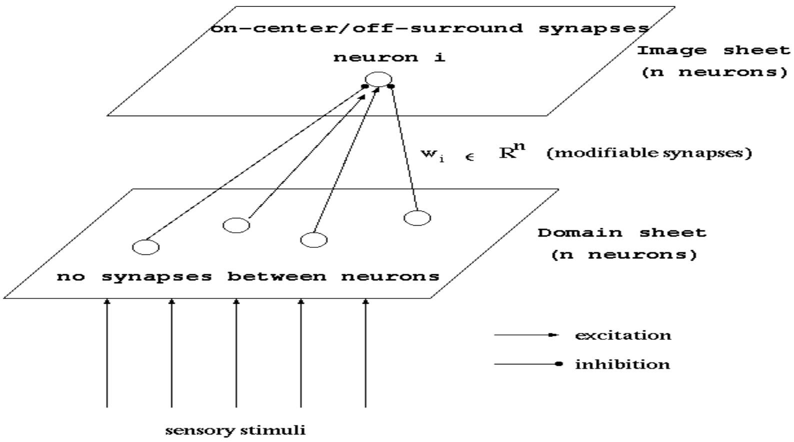

Figure 1. A Self-organizing map with two bidimensional sheets of neurons.

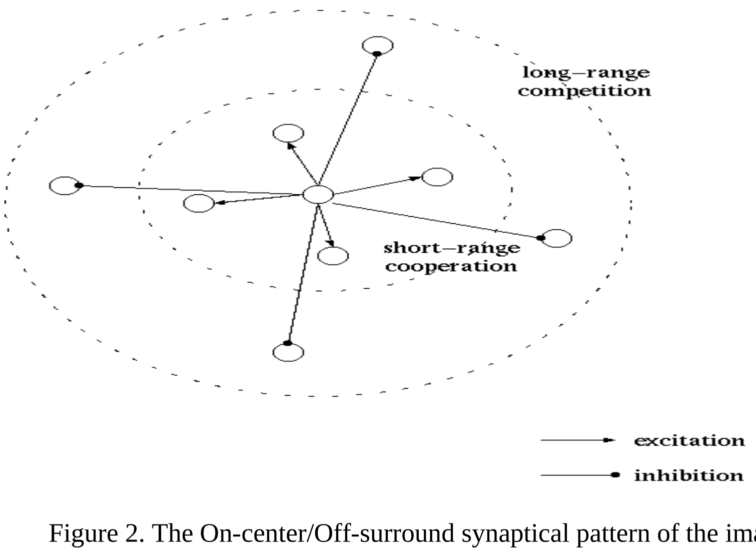

Figure 2. The On-center/Off-surround synaptical pattern of the image neuronal sheet.

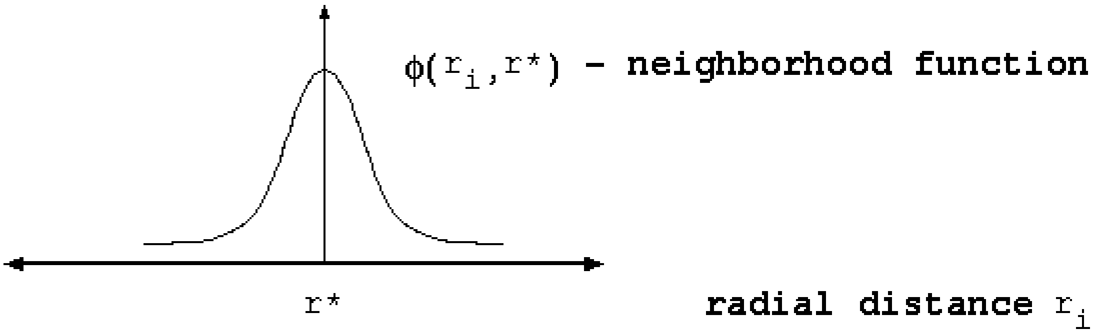

Figure 3. The neighborhood function representing the steady-state concentration of a neural growth factor.

The initial dispersion of the gaussian, σ_0, is high, representing that all the neurons in the image are considered neighbors. This allows the modification of the randomness of the initial synapses to a more organized pattern, where neighborhood is of capital importance. Every time-step ***l*** in which another stimulus is presented to the neural network domain, the neighborhood shrinks a bit, gradually giving the map a local organization.

The way the learning rate decreases and the neighborhood shrinks is fundamental to the development of the map. A faster decrement in the learning rate does not give enough time for the synapses to change, and so the randomness of the initial synaptic pattern is consolidated at the end of the process. When neighborhoods shrink rapidly, the level of neuronal cooperation necessary to produce maps is insufficient and neighborhood relationships are ill-defined at the end of the simulation. Indeed, the neighborhood function may be likened to the steady-state concentration profile of a neural growth factor in the neural tissue. When dynamical equilibrium between neural growth factor release and metabolization is accomplished in every region of the tissue, due to the diffusion process, a concentration profile that asymptotically decreases with radial distance is attained (see Figure 3). The parameter σ_0 represents the amount of neural growth factor released by the neurons at the beginning of the neurodevelopment process.

As plasticity is always happening in our brains, if the parameter σ which controls the rate of synaptic alteration is kept constant, the map will represent a cortex which is capable of changes during a subject's entire lifetime.

5. Simulation Results

A self-organizing neural network with its two bi-dimensional sheets composed of 400 neurons each was developed for computer simulation, as shown in Figure 1. A set of different stimuli, symbolized by the geometrical markers and representing different concepts or ideas, was repeatedly presented to the Domain sheet of the neural network. Due to the feedforward connections between the Domain and the Image sheet, every stimulus presented to the Domain is projected to the Image. Initially, the synapses are randomly generated and therefore the stimuli presented to the Domain sheet are projected to random positions at the Image layer. While the stimuli are repeatedly presented to the neural network, synapses change and a map-like structure develops at the Image layer. Similar stimuli, representing nearly associated or similar concepts, when presented to the Domain layer, lead to the excitation of neighboring regions in the Image neuronal layer. On the other hand, different stimuli, representing dissimilar or not directly associated concepts or ideas, when presented to the self-organizing neural network, will excite neurons at distant regions at the Image sheet. This is what we call a semantic map.

The purpose of our simulations is to show that different maps arise when dopaminergic modulation controls the synaptic formation process. In fact, varying the parameters responsible for the signal-to-noise ratio results in maps that represent the concepts or ideas in a way that can be likened to the delusional, creative, and disorganized thought. To simulate the signal enhancement promoted by the dopaminergic activity, a threshold θ is associated to every neuron at the Image sheet (Servan-Schreiber, 1990). When the total signal input (the sum of all the incoming stimuli weighted by the synapses that bring them) coming from the Domain layer to an Image sheet neuron, exceeds the threshold, this neuron is considered to be excited. Increasing or decreasing the threshold will promote the effect of dopaminergic enhancement or dampening of the incoming signal. The simulation of noise is simply obtained by adding to the stimulus a random number in the interval $[-p, +p]$, where p is a percentage of the stimulus value (Servan-Schreiber, 1990). The parameters θ and p allow us to realize any simulation desirable with total control flexibility over the signal-to-noise ratio.

In a first simulation experiment, a semantic map was allowed to develop from the self-organizing neural network when ten stimuli, representing ten different concepts or ideas, were repeatedly presented to the Domain layer with no noise and a predefined signal level θ of 0.999. This map is represented in Figure 4 and will stand as a reference for future comparisons. Note that the similar stimuli • and * were mapped into neighboring regions of the Image neuronal layer while, for example, the very different stimuli represented by **+** and | were mapped into the opposing corners of the Image sheet. This simulation experiment was done to show that the map was well-formed for these ten concepts or ideas with a clear signal and no noise, and will serve as a reference.

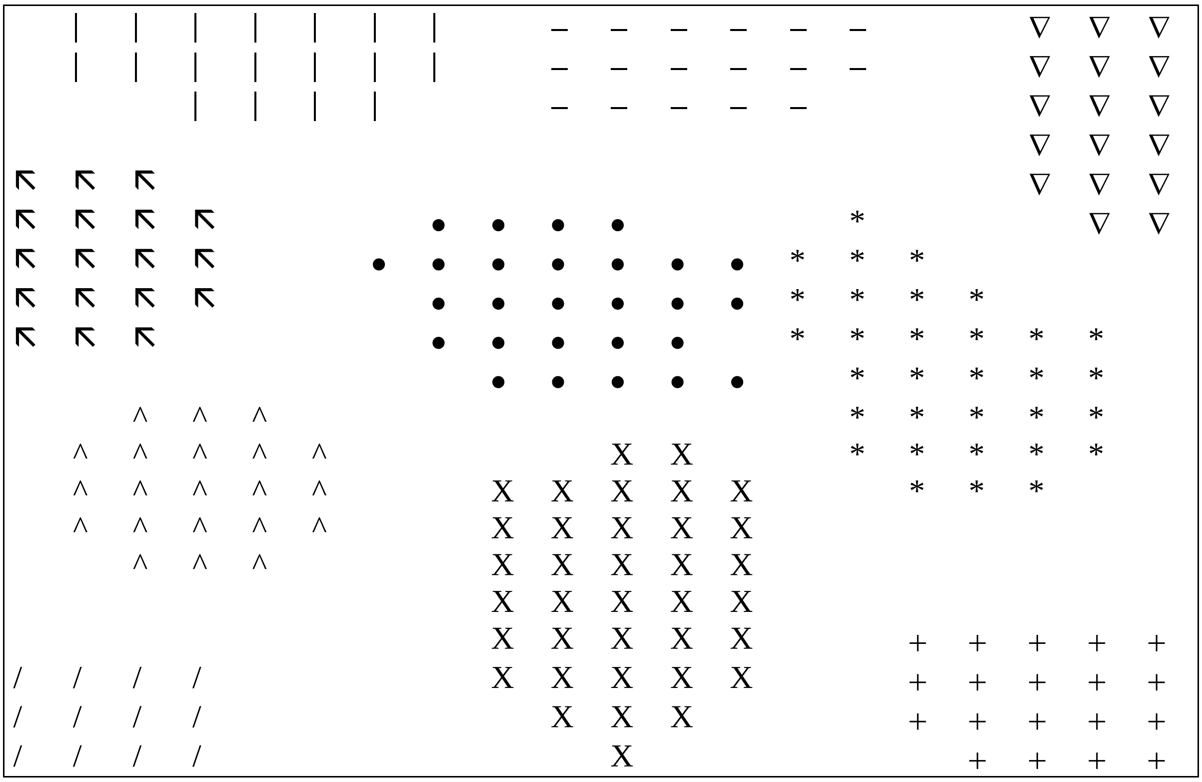

Figure 4. A reference map with ten different concepts represented on it.

In a second simulation, the Domain sheet of this already well-formed map was excited by the single stimuli represented with a •. The dopaminergic modulation was changed in this simulation with the addition of a noise level *p* of 10%. The resulting Image layer map can be seen in Figure 5. Note that with the addition of noise, the stimulus • expanded its representation, exciting neurons outside its original region at the Image layer and invading the region associated to the concept represented by *. This can be interpreted as if the increase of noise level, or equivalently the decrement of the signal-to-noise ratio, was capable of promoting the association of the different, but similar, ideas or concepts • and *, neighbors in the map.

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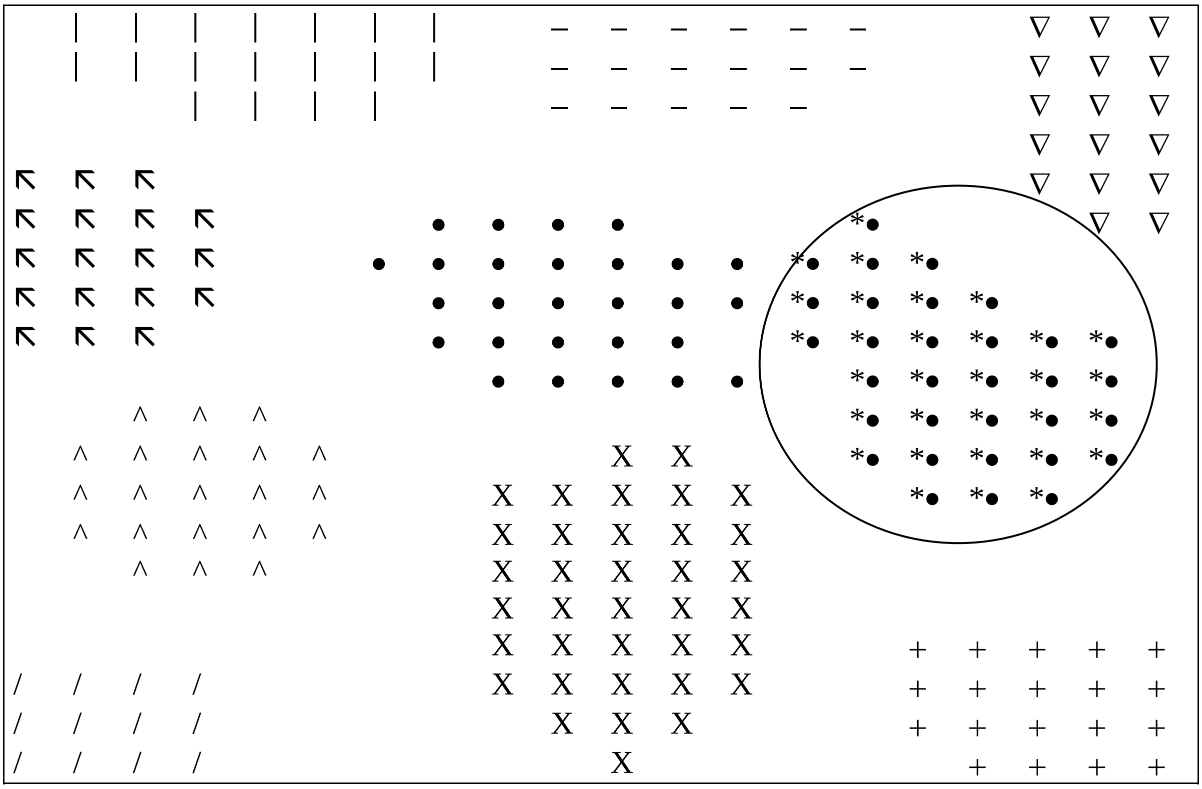

Figure 5. The central idea • (thesis) is associated with a neighboring idea * (antithesis), leading to the formation of a pattern that is the conclusion of the thinking process, or the synthesis.

Much of our reasoning about the functioning of our model can be understood as a mechanism of association of ideas. Indeed, when a stimulus (endogenous or exogenous) elicits a central idea, that we will call here a "thesis", other ideas, that corroborate or refute the thesis, are spontaneously elicited. Let us call these spontaneously elicited ideas the "antitheses." Because the thesis and the antitheses are elicited at the same time, they are temporally associated, and the final result of this simultaneous presence is the weighted sum of their influences, with the emergence of a final pattern that we will call the "synthesis", or the conclusion of the reasoning process. If we assume that the "normal" thought is the triggering of a thesis that elicits a group of antitheses which will be weighted (pondered) together to generate a synthesis, then, for the occurrence of "normal" thought, it is necessary to have some level of noise, i. e., a relatively lower dopaminergic modulation of the signal-to-noise ratio.

In the next simulation, the noise level was increased from 10% to 170%, and the same procedure followed in the second experiment was repeated. The result is shown in Figure 6. Note that now the central stimulus • (thesis) has excited many neurons outside its original representation, invading areas where other stimuli were represented. In our model, this means that a central idea (thesis) has been associated with many other ideas (antitheses) generating a pattern that we can liken to a creative thinking process. If, in "normal" thought, a central idea (thesis) is associated to a few other neighboring and similar ideas (antithesis), in creative thinking, this same central idea will be associated to different, normally not associated, ideas. The process of making associations between a central stimulus and distant ones resembles the formerly reviewed theories of creativity, where concepts like "loosening of associations", "divergent-thought", "ability of making unusual relationships", "flexibility of mental organization", "a momentary freedom from stereotyped and conventional scenes", "broadening of conceptual boundaries", "unfocusing of attention", and some other similar concepts are always present. As a consequence, it is necessary to have a higher level of noise, or equivalently, a lower dopaminergic modulation of the signal-to-noise ratio, for the occurrence of creative thinking, as experimentally observed in reference (Spitzer, 1997).

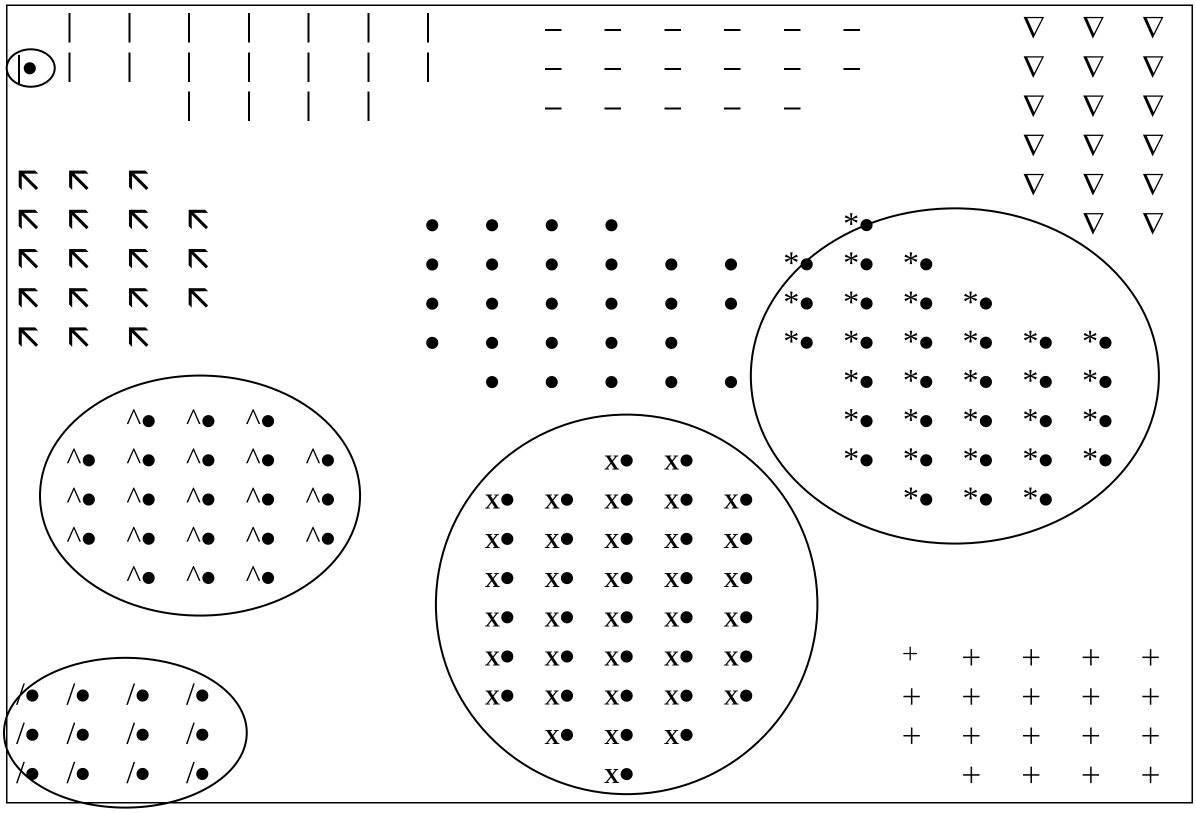

Figure 6. The central idea • (thesis) is associated with distant ideas (antithesis), leading to the formation of a pattern that can be likened to the creative thinking.

In the same way that coarse rather than focused semantic activation is strongly related to schizophrenic thought and creative thinking (Leonhard, 1998), the model presented here can show the subtle border between creativity and disorganized thought. Indeed, if the signal-to-noise dopaminergic modulation is still more reduced, with an increase in the noise level p from 170% to 200% in the model, and the same simulation experiment is repeated, a new pattern will appear in the Image layer of the neural network, as can be seen in Figure 7. Note that this increase in noise was sufficient to make the same stimulus • invade other distant areas that it had not invaded in the earlier simulations. This means that the central idea (thesis) elicits a plethora of other ideas (antitheses), resulting in a new pattern that represents a synthesis, where all the ideas are present and associated among themselves. It is not possible in this case to know what is the central idea and what is laterally associated. The synthesis lacks a coherence in relation to the thesis, because all the associated ideas are equally present and weighted, and opposing and corroborating ideas have the same influence over the conclusion (synthesis). The synthesis encompasses any idea, independently of its contents or proximity in relation to the thesis. We can say that a synthesis like this represents a disorganized thought, that follows no direction and has no consistent meaning. In other words, when noise is higher, the association of ideas becomes more flexible and the creative thought degenerates to disorganization. The border between creativity and disorganization is obviously not clear, as seen in the ideas reviewed at the beginning of this paper. As a consequence, the precise level of dopaminergic modulation of the signal-to-noise ratio that distiguishes geniality from illness can not be determined. Actually, the model has shown up to now that there is a continuum ranging from normal thought to the disorganized one, passing through what we call creativity. In the next simulation, this continuum will be shown to encompass even the delusional thought.

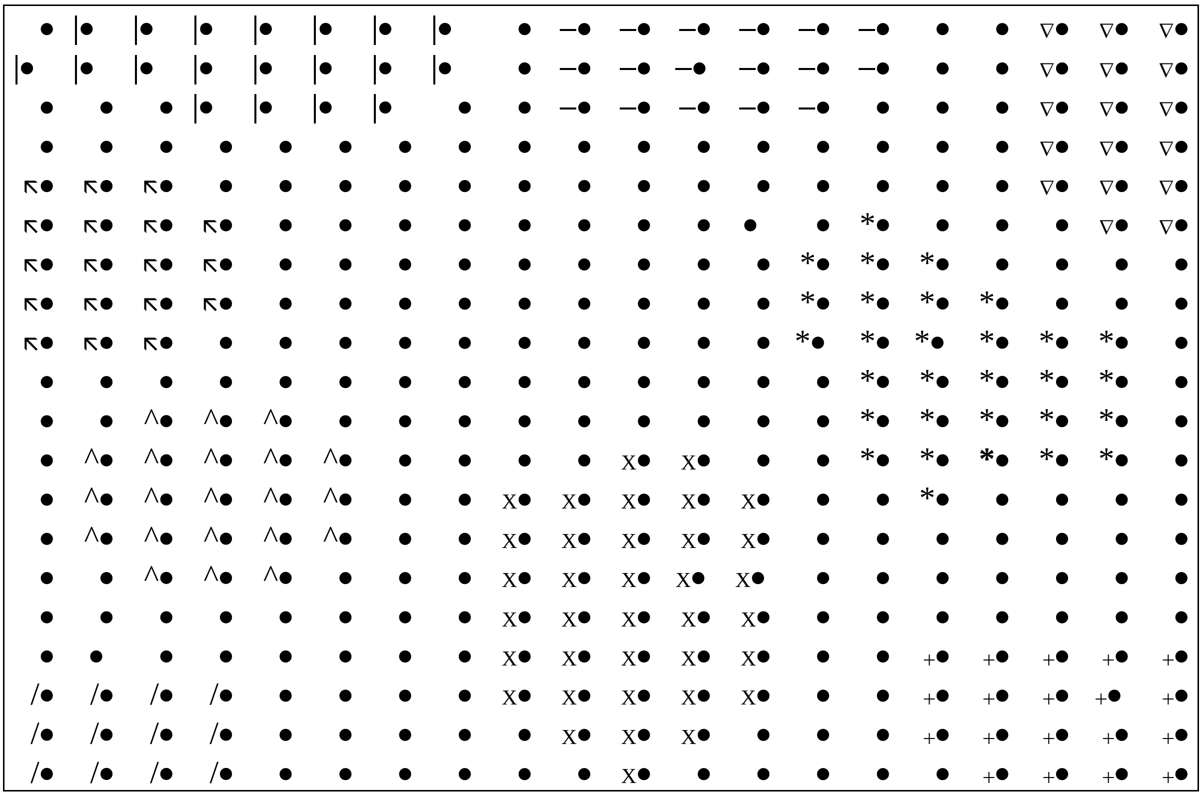

Figure 7. The central idea • (thesis) is associated with all ideas, leading to the formation of a pattern that can be likened to the disorganized thought.

Since dopamine regulates the signal-to-noise ratio, it is necessary for realistic simulations to calibrate these two important variables, signal and noise, to generate values for this ratio that are significant to our experiments. In the previous simulations, noise was gradually increased promoting the association between a central idea and more and more distant concepts. In the next and last experiment which we present, noise was kept constant at a value p of 5% and the signal level θ was increased from 0.999 to 0.9995. The same ten stimuli were presented to the neural network and the central idea , •, had its signal level increased. The neurons excited at the Image sheet are shown in Figure 8. Note that, in comparison with the original map described in Figure 4, the area occupied by the ideas has shrunk. This shrinking process makes the representation more focused and the associations among the ideas represented more unlikely to occur. The stimulation of the neural network with a stimulus representing an idea (thesis) does not elicit the concomitant excitation of neighboring ideas (antitheses) because the shrinking process has separated the regions from one another. In this situation, the synthesis becomes equal to the thesis because there are no antitheses to corroborate or refute the central idea (thesis). The “normal” thought process of weighing many ideas with different influences to achieve a conclusion does not happen any more. It is possible to liken this phenomenon with the delusional thinking, because the absence of antitheses does not allow the embedding of doubts, resulting in the character of unquestionable certainty and incorrigibility of delusions.

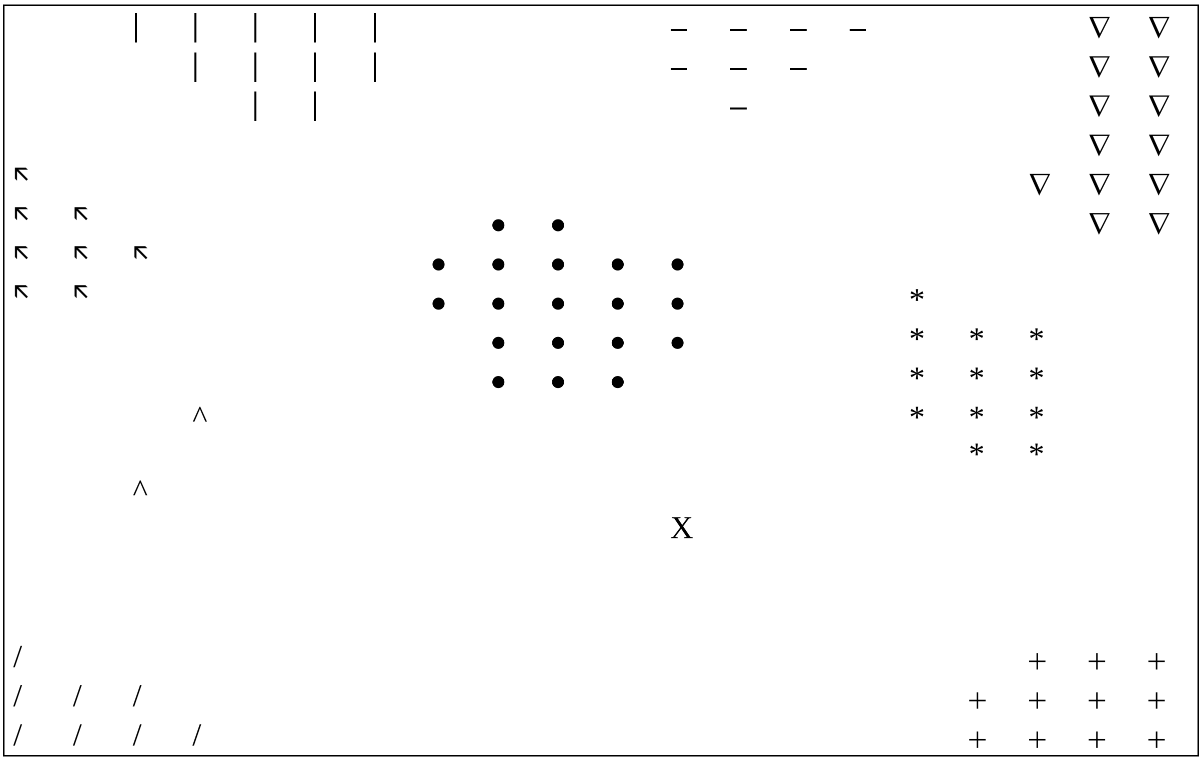

Figure 8. The stimulation of the neural network with a higher signal level leads the ideas to shrink their original region in the Image layer, hindering their association. Without associations, the synthesis becomes the thesis and the antitheses are not considered or pondered. This map seems to represent a rigidity of thought or a delusional thinking.

These simulations show that the model unifies the many-faceted phenomenon of normal and abnormal thinking. Different thinking processes are viewed so as to correspond to possible positions over a one-dimensional continuum, where the signal-to-noise ratio is the measure. At one extreme of this line, where the signal-to-noise ratio is high, the semantic map becomes more focused in the representations of ideas, resulting in delusional thinking. At the other end of the linear continuum, where the signal-to-noise ratio is low, the excessive noise promotes unusual associations among ideas, resembling the disorganized thought. The "normal" and the creative thought processes are positioned between these two ends, depending on the noise level, as can be pictorially shown in Figure 9.

Conclusions

Based on experiments that suggest the dopaminergic signal-to-noise modulation of the CNS neurons, and hypothesizing the existence of semantic cortical maps that would represent concepts or ideas, we developed a self-organizing neural network model to unify the different thought processes into a single neurocomputational substrate. We performed simulations varying the two main control parameters of the dopaminergic modulation, which are the signal and the noise levels carried by the neurons from the input to the output and throughout the neural network. Stimuli representing different ideas or concepts were mapped in a self-organized way, and this map was taken as a reference for the other simulations. These simulations were performed simply, by stimulating the neural network input layer with a single stimulus and observing the corresponding areas of the output layer that were excited, as in an associative process. At each simulation, the signal-to-noise ratio was varied and different patterns emerged at the output layer.

Basically, the stimulus used in the stimulation of the input layer was compared to a trigger of a central idea (or a thesis) at the output layer that, depending on the signal-to-noise ratio, invaded or not the neighboring areas that represented other ideas (antitheses). Assuming that the thought process (or synthesis) is the total pattern elicited at the output layer of the neural network, as the result of the weighted influence of every area (thesis and antitheses) excited, the model could show how the "normal" and "abnormal" thinking are generated. In addition, it was shown that the borders between the different thought processes ("normal" or "abnormal") are fuzzy because, actually, there are no rigid borders, but a continuum. The transition from a high signal-to-noise ratio to a low one results in a qualitative change of the reasoning process, ranging from delusion to disorganization of thought, and passing through what we may call "normal" and creative thinking. The model unifies the qualitatively different thinking processes into a neurobiologically-based substrate, and also shows that these processes define a continuum with gray zones where their differentiation is difficult or impossible. Although biologically plausible, in agreement with many aspects described by psychodynamical clinical experience and experimentally based on simulations, the model is very schematic and far from explaining the complexities of human thinking. Nevertheless, it seems to be a good metaphorical and unifying view of the many facets of this phenomenon, usually studied in separate settings.

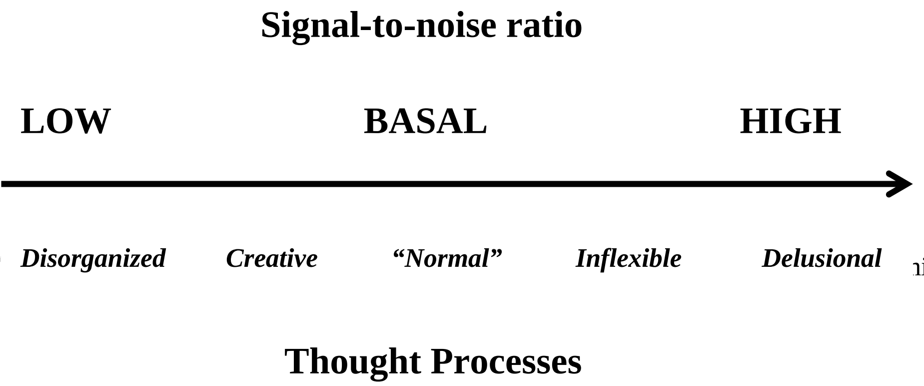

Figure 9. T ... inergic modulation.

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