2.2 Modelling Self-Organization and Performance of Neural Nets

How are Nervous Structures Organized?

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1. From Cybernetics to Synergetics

In the view of cybernetics the brain is an appropriately structured nervous net for the processing of signals; understanding the brain is identical with knowing the connection pattern and its function. The corresponding view in computer science identifies artificial intelligence with appropriate programs, executed on the computer. Computer chess, artificial speech production and pattern recognition testify to the success of the approach. In both cases, brain and computer, the process of organization responsible for the genesis of connection pattern or program is considered as an independent issue. It is in the style of cybernetics to assume that the genome of the individual contains a blueprint for the wiring of its nervous system, and that during ontogenesis this information is simply translated from one form into another. Thus, phylogeny can freely program nervous connectivity to its requirements.

This simple view is not viable, as can be seen from several lines of evidence. Firstly, our genome is by far not sufficient to freely program the $10^{14}$ connections in our brain. It evidently only selects from a much narrower universe of patterns. Secondly, brain structure in higher vertebrates is variable from individual to individual; it is highly adaptive in response to small lesions; and it flexibly deals with alterations in the environment. Consequently there is no invariant connectivity diagram which could be the subject of science; and even if there was, an irregular pattern of $10^{14}$ connections is beyond scientific analyzability. Similarly in artificial intelligence: the program needed to model human behaviour is beyond our capabilities, for quantitative reasons alone.

There can only be one conclusion from this argument. Science has to understand the process of brain organization before it can understand brain structure. Similarly, artificial intelligence needs but one program: one which is able to formulate problems and their solutions. (A program which emulates human behaviour anyhow would have this capability.) Several principles of organization have
been formulated in physics and biology. It has been shown in the past that they can be applied to organization in ontogeny and during function of the brain. I will here introduce some of the essential ideas on an abstract level, and will then apply them explicitly to a specific ontogenetic problem which has been considered a paradigm of organization in the brain for many decades.

2. Organization by Cooperativity and Selection

Organization is a process which takes place in a system that is composed of a multitude or a continuum of interacting constituent elements, and by which an initial 'unorganized' state is transformed into a final 'organized' state. The transformation is brought about as an effect of the interactions between the constituent elements, not as the result of a physically pre-existing and detailed master plan. The meaning of the terms 'organized' and 'unorganized' varies according to the system under consideration and a general characterization cannot yet be attempted. In simple cases the terms may refer to 'chaotic' and 'ordered', or to 'homogeneous' and 'patterned'.

The unorganized state, which on the average is in equilibrium, is destabilized by a mechanism by which small deviations from the initial state (fluctuations) self-amplify. (The mechanism is part of the elemental interactions or of their inner dynamics.) Fluctuations in different 'directions' are possible in one point. Fluctuations in different points of the system can interact in the sense of mutual enhancement (cooperation) or of mutual attenuation. A whole constellation of fluctuations in the system (a pattern) can be rated by the total degree of cooperation, or inner consistency. Certain patterns may be structured such that they grow (or decay) in amplitude without changing in form (i.e., with fixed ratios between the amplitudes of the constituent fluctuations). They are then called eigen-patterns or modes.

Different modes can be superposed in the system. (This superposition may, for instance, be realized in the sense of a linear approximation, or in a probabilistic way.) Certain of the superposed modes compete with each other (in the simplest case the sum of their amplitudes is fixed). As a consequence only the modes with the highest inner degree of cooperation can grow, the others have to decay. This competition mechanism corresponds to Darwinian selection. The degree of cooperation of the modes plays the role of Darwinian fitness. Eventually only one mode (or a set of mutually cooperating modes) survives, presumably that with the highest degree of inner cooperation. This pattern constitutes the organized state. It is globally ordered in the sense of a system of consistently intermeshing local interactions, and it is stabilized by these interactions against small disturbances.

There is a hierarchical structure to organization, as is already made evident by this discussion: modes may be regarded as fluctuations on a higher level, their cooperation and competition forms a new system of interactions, and a cascade of organization processes can be imagined.

Often, especially in physics, the organizing system is characterized by a homogeneous array of inner interactions and by the shape of a boundary. Also, the system may be influenced by an externally controlled globally ordered force field. Both the shape of the external force field and that of the boundary are decisive in
selecting possible patterns in the system. There is a strong element of teleonomy in organizing systems, since the possible final configurations are preexisting as idealized mathematical forms; the detailed dynamics of the interactions and the historical development can only select between them. (This point, like the others, will be exemplified below.)

The contrast of this concept of organization to the cybernetical (pseudo-) concept of organization is extreme. In no sense are the organized states arbitrarily programmable, nor are they preformed in any palpable or coded form. The organized state is produced by the local interactions within the system, without there being the need for any global or centralized control.

3. Organization in the Nervous System

There are various levels on which the above scheme of organization can be applied to the nervous system. The general format of organization during its ontogenesis is that of an evolving net of interconnections. An unorganized initial state is characterized by an unspecific distribution of synaptic interconnections (or of probabilities of connection). In the organized final state only comparatively few connections 'of the correct type' survive. In other words, a fuller graph is converted into a sparser graph. The important variables are weights characterizing the individual connections. They can be interpreted as strength of connection (synaptic efficacy), or as probability of connection in a dynamic process of making and breaking of contacts. The interactions between weight variables are mediated by nervous signals, which in turn are transported by the connections. An individual weight is controlled by the two signals available to it, presynaptic and postsynaptic. Organization in any part of the nervous system is influenced also by the signals flowing into it from its environment: the rest of the nervous system including the sense organs.

What are the 'connections of the correct type'? In the context of our present discussion the surviving connections must form cooperating constellations. Several connections converging on one target cell certainly do cooperate if they all excite the cell at the same time. This situation can arise if the different connections all form part of short alternative pathways from the same source cell to the same target cell, see fig. 1. From the point of view of one of the connections the situation is characterized by a disproportionately large effect of the incoming signal on the target cell. This is the situation to be stabilized. Consequently, an excitatory connection has to grow in weight if it senses coincidences between presynaptic and strong postsynaptic activity. On the other hand, in order to keep individual cells from dominating the whole network, the combined weights emanating from one cell should be limited; similarly, in order to keep neurons from being continuously saturated, the combined weights leading to them should be limited. These limitation rules lead to selection between different interconnection patterns.

Fig. 1 The indirect synaptic connections between cells a and b cooperate with the direct one
Genetic information may determine this process in two ways, by providing general rules in terms of cellular mechanisms, and by staging individual organization processes with the help of appropriate starting and boundary conditions. For this latter task the widely discussed arsenal of morphogenesis may be used, division of the tissue into compartments and into cell classes with different chemical and morphological specialization (dendrite and axon formation), of which also the timing is controlled genetically. In addition, fibre growth may be directed by 'addresses' specific for compartment and cell class.

4. The Establishment of Topological Projections

A particular example of an ontogenetic organization process in the nervous system has attracted the attention of scientists for a long time, and their combined efforts have turned it into an important paradigm: the establishment of retinotopic fibre projections from the eye to the brain in vertebrates. This example has the advantage of being conceptually simple, generic, and easy to access experimentally. Early in embryonic development the retinal ganglion cells put out fibres which grow to the optic tectum (among other structures). At first the connection pattern is rather indistinct (at least in some species). Later in development the projection is retinotopically structured: each retinal cell projects to only a small area of tectum, and neighbouring retinal cells project to neighbouring points of tectum. What are the mechanisms responsible for this development?

Various theories can be advanced to account for the normal development. In order to select among them, many ingenious experiments have been performed in which normal development was somehow disturbed, or in which the already developed system was partly destroyed, modified, and allowed to regenerate. For review see [1]. Only one theory survived experimental test. It was first formulated in [2]. It postulates two mechanisms. A global one, which is responsible for a rough placement of retinal fibres in the correct general region of the tectum (gradients of chemical markers could furnish the guiding signals for it). And a local mechanism, which establishes precise topological order. (Such a mechanism is shown below to be sufficient on its own.) The local mechanism is formulated in terms of the ideas outlined in section 3, supplemented by preexisting short-range fibre systems within retina and within tectum. As a consequence, pairs of retino-tectal fibres cooperate if they connect neighbouring cells to neighbouring cells, compare fig. 1, where the left column may stand now for retinal cells, the right for tectal cells. The next sections contain a specific formulation of the local mechanism and a description of the organization process in mathematical terms. It is an outline of the more detailed treatment given in [3].

5. The Differential Equation

For the sake of simplification, treatment is limited to a 'retina' and a 'tectum' in the form of one-dimensional chains of nerve cells, the number of which is N in both cases. This has the advantage that the configuration of all connection weights between retina and tectum can be visualized in the form of a matrix, see fig. 2, 3 or 5, and that certain mathematical complications are avoided. Another simplification is introduced by cyclically closing both chains of
cells. This avoids complicated border effects. The desired final result of organization is a concentration of all weights into one of the two possible diagonal patterns in the matrix.

According to the general ideas sketched above, the weights are controlled by cellular signals. These spontaneously arise in retinal cells, are exchanged between neighbouring retinal cells (over the preexisting short-range connections there), are conducted to tectum with an efficiency determined by the connection weights, and are exchanged between neighbouring tectal cells. The mathematical description of the system therefore should consist of two tiers of equations, one for the signals, one for the weights. An exact treatment of such a system would be rather involved (especially in view of the nonlinear nature of signal processing). It is, however, possible to write down a simple autonomous equation for the connection weights, in which the effect of the signals is expressed implicitly. This equation was developed on the basis of experience with computer simulations and analytical calculations.

Let the real number $w_{ir}$ be the weight of the fibre connecting the retinal cell $r$ to the tectal cell $i$. The weights define a real function $w$ on the domain $0 \leq r, i \leq N$. The differential equation has the form:

\[ \dot{w} = \alpha + w \cdot Cw - w \cdot B(w + w^* Cw), \]

or, written in component form:

\[ \dot{w}_{ir} = \alpha + w_{ir} \cdot C_{ir}(w) - w_{ir} \cdot B_{ir}(w + w^* Cw). \]

In this equation, $\alpha$ is a positive parameter which describes the unspecified production of new synapses. $C$ is a convolution operator with a bell-shaped kernel in $r$-$i$ space, see fig. 2. The value of this kernel for a given distance of two fibres in retina and in tectum expresses the degree of cooperation of the two fibres. $C(w)$ is a smoothed version of the matrix $w$. $C_{ir}$ acts as a rate constant for the 'autocatalytic' growth of the weight $w_{ir}$, expressed by the second term on the right-hand side of (1). The operator $B$, taken at the point $i, r$, forms the mean of all elements in the row $i$ and in the column $r$ of its argument matrix. The argument of $B$ is the matrix of the growth rates, which form the first two terms of the equation. The term involving $B$ expresses the competition between one fibre and all those others which come from the same retinal cell (a row of the matrix), and which go to the same tectal cell (a column of the matrix), indicated as a cross-shaped region in fig. 2.

![Fig. 2 Interactions in the matrix of connections. The symbol in the column $r$ and the row $i$ represents by its size the weight of the connection between cells $r$ in retina and $i$ in tectum. The circle symbolizes the cooperative help received by connection $w_{ir}$ in the center from the surrounding ones, with a weight given by the kernel $C$. The cross-shaped region contains all connections which compete with $w_{ir}$, as described by the $B$ term.](image-url)
It is convenient to discuss equation (1) in a slightly rearranged form, with all terms involving $\alpha$ collected into one term, (note that $B$ is a linear operator):

$$\dot{w} = -\alpha(w-1) + w(C(w) - B(w)C(w)).$$

The symbol 1 is used for a matrix filled with 1's, i.e., homogeneous distribution of contacts between all retinal cells and all tectal cells. The term involving $\alpha$ describes an exponential decay of $w$ towards 1. Also the second term has the stationary solution 1, since $B(1)=1$ ($B$ is an averaging operator) and $C(1)=1$ (with an appropriate normalization, which can always be attained by changing the unit of time). In distinction to the first term, however, the second term destabilizes the solution 1.

In order to understand the second term of (2) let us discuss a simple model equation which plays a role in evolution theory [4]:

$$\dot{x}_i = x_i(f_i - \Sigma x_j f_j).$$

The quantities $x_i$ can be interpreted as the population sizes of different species in an ecosystem. The $f_i$ are their Darwinian fitnesses in a struggle for limited resources. Each species $x_i$ by itself would grow in number exponentially with a rate constant $f_i$. The second term in the bracket is the sum of all individual growth terms and stabilizes $\Sigma x_i$ at the value 1. The second term is the weighted average of all fitnesses. The bracket acts as an effective rate constant and is positive for species $i$ only if $f_i$ is above average. If it is below, the species will decay in number and will eventually die out. The subtracted average fitness monotonously grows because the larger fitnesses are weighted more and more. Eventually only the species with maximal fitness survive(s).

Analogously, the second term in (2) describes a growth of those 'species' $w_{ir}$ which have a 'fitness' $C_{ir}(w)$ above the average expressed by the $B$ term. As $C_{ir}$ describes a weighted sum over the neighbours of $w_{ir}$, weights will grow in regions of $w$ with increased density. In comparison to (3), the situation is complicated by the fact that the 'fitnesses' $C_{ir}(w)$ are variable and introduce interactions between species, that the $B$ term can only approximatively be interpreted as an average, and that this average extends not over all 'species' $w_{ir}$ but only over those in the same row and in the same column. It is intuitively clear that the interactions depicted in fig. 2 favour a diagonal chain of weights, i.e. a retinopitoc configuration.

6. Linear Analysis

In order to apply the scheme of organization outlined in section 2, equation (1) has to be rewritten in terms of the deviations $v = w-1$ from the stationary solution:

$$\dot{v} = -\alpha v + C(v) - B(v) - B(C(v)) + Q(v) + K(v).$$

$Q$ and $K$ are quadratic and cubic terms the explicit form of which is not of importance here. The linear term may be abbreviated $L(v)$. For small deviations $v$ the higher-order terms $Q$ and $K$ are small. A good first approximation is therefore obtained by solving the linearized equation $\dot{v} = L(v)$. Any such solution can be expanded in terms of a basic set of solutions, the eigen-patterns or modes. A mode has the property $L(e) = \lambda e$, with a certain number $\lambda$, the
eigenvalue. One special solution of the linearized equation is then \( v(t) = \exp(\lambda t)e \). Such a solution will grow or decay depending on whether \( \lambda \) is positive or negative.

There are as many modes of \( L(v) \) as there are components, i.e., \( N^2 \). Their form is determined entirely by the symmetry of the problem (which we chose to be cyclic). This is an example of the teleonomy we referred to earlier. The modes can be given explicitly:

\[
\eta_k^ \ell = \exp(2\pi i (k\ell + (\ell)/N)),
\]

where \( k \) and \( \ell \) are indices running from 0 to \( N-1 \). For \( k = \ell = 0 \) we have the constant function 1. For the other values the modes are periodic complex harmonics in the connection matrix, see fig. 3 for a few examples. If one denotes the eigenvalues of the operator \( C \) by \( \gamma^k \)

\[
\zeta (e^{\gamma^k}) = \gamma^k e^{\gamma^k},
\]

the eigenvalues \( \lambda^{k \ell} \) of \( L \), which are found simply by applying \( L \) to the modes, are:

\[
\lambda^{k \ell} = \begin{cases} 
-\alpha - 1 & \text{for } k = \ell = 0, \\
-\alpha + (\gamma^k - 1)/2 & \text{for } k = 0, \ell \neq 0 \text{ or } k \neq 0, \ell = 0, \\
-\alpha + \gamma^k & \text{otherwise}.
\end{cases}
\]

It is easy to see in which way the basic interactions in (1) or (2) determine the order of eigenvalues. The cross-shaped sum in the

Fig. 3 A few modes of the linearized equation, \( \dot{v} = L(v) \). Open symbols represent negative weights. The upper row contains vertical modes of the two lowest spatial frequencies, and a horizontal mode. All vertical and horizontal modes are heavily damped by the \( B \) term. The lower row contains the two diagonal modes, whose eigen-value surpasses all others, and an oblique mode.

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operator B selectively damps all modes with vertical or horizontal waves. The B term is responsible for the -1 in the first line and the -1/2 in the second line of (7). It is ineffective in oblique modes. The C operator contributes the terms involving \( \gamma^+ \) and is largest for the lowest spatial frequencies, which are least damped by the convolution in C. The \( \alpha \) term damps all modes in the same way, as is evident from (2).

We now require that the kernel of the convolution operator C be symmetric, hence its eigenvalues are real and \( \gamma^+ = \gamma^+ \). In addition we require that the largest of these eigenvalues be

\[ \gamma = \gamma^+ \]

which is equivalent to the bell-shape of the kernel. These properties allow the introduction of real modes (sine and cosine waves), and secure that the largest of all eigenvalues of L is

\[ \lambda = \lambda^+ = -\alpha + \gamma. \]

It belongs to the four 'diagonal modes': those of the fundamental frequency and the two diagonal directions in the \( \omega \) square, each with two phases. All the other eigenvalues are enclosed in the interval \([-\alpha-1,-\alpha+\gamma]\).

With the help of the control parameter \( \alpha \) (the unspecific growth rate of contacts) the spectrum of L (7) can be shifted as a whole. It therefore can be arranged that only the maximal eigenvalue \( \lambda \) is positive and all others are negative. Under that condition only the amplitudes of the diagonal modes will grow according to the linearized equation, all other modes will decay. This is a very important result, as it ensures that the desired diagonal patterns are selectively amplified by the system and all other modes are damped, at least for small deviations \( \nu \). We refer to the diagonal modes as principal modes, and to all the others as ancillary modes.

It is useful here to refer back to the general scheme of organization introduced in section 2. The system of interactions between the constituent elements of the system (the connections), as introduced by the operators C and B in equation (1), have turned out to be cooperative, since they lead to self-amplifying fluctuations (regions of higher or lower density in \( \omega \)) which can consistently mesh with each other to form globally ordered patterns, or modes. Different such modes can be superposed in the system and differ in their degree of intrinsic cooperation (the eigenvalue). The linearized equation \( \dot{\nu} = L(\nu) \) describes no interactions between the different modes. These are mediated by the non-linearities of the equation (Q and K in eq. 4), the effects of which will be described in the next section.

7. Non-linear Interactions up to Third Order

The linear discussion leaves out important effects - stabilization of the amplitudes at finite values and interactions between modes - but it serves as a basis for an important transformation of the system. An arbitrary state \( \nu \) of the system can be decomposed into a sum of linear modes:

\[ \nu = \sum \zeta_l \cdot e^{il} \]  

with time-dependent amplitudes \( \zeta_l \). Since (8) is a Fourier series, it can be inverted. Consequently, if (8) is inserted into (1), the
resulting equation can be resolved for the time derivatives of the amplitudes $\xi'$. This gives a system of equations which is equivalent to (1) and contains as many variables. However, it is now separated into stable and unstable variables, and it can be simplified enormously by assuming that the amplitudes of the ancillary modes (i.e., those with negative eigenvalue) have decayed and stay near to the values dictated by the amplitudes of the principal modes. This assumption is referred to by physicists as the adiabatic approximation. The amplitudes of the ancillary modes can then be eliminated from the system, which is a tedious procedure, but straight-forward if the precision is limited to third order in $v$ (see [3]). The four principal modes can be described by only two variables, since the phases of the diagonals do not shift in time, according to the differential equation. It can be assumed without restriction of generality that they are centered as in Fig. 3. The whole system then reduces to two equations for the amplitudes $\xi'$ and $\eta'$ of the two diagonals:

$$\begin{align*}
\xi' &= (\lambda - \gamma (a^2 + b^2)) \xi \\
\eta' &= (\lambda - \gamma (a^2 + b^2)) \eta,
\end{align*}$$

(9)

where $a$ and $b$, with $b > a$, are numerical constants and are combinations of $\alpha$ and the first few eigenvalues of $C$. When the decaying modes are totally neglected, $a$ and $b$ take on the values 2 and 4, respectively. With reasonable assumptions for the value of $\alpha$ and the shape of $C$ both $a$ and $b$ remain positive. The amplitudes $\xi$ and $\eta$, as long as they are small, grow independently of each other with a rate constant $\lambda$. Later, control is taken over by the nonlinearity of third order. Since $b > a$, there is a competition in which the larger of the two amplitudes has an advantage, so that it eventually wins. Equation (9) can be written in the form $\xi' = -\partial V/\partial \xi$, $\eta' = -\partial V/\partial \eta$ with a potential $V$ of fourth order in $\xi$ and $\eta$. The shape of $V$ is shown in Fig. 4. It shows that there are only two stable stationary states of the reduced system, each a pure diagonal. The original symmetry of the system with respect to the orientation of the diagonal is broken spontaneously.

In the real case of two-dimensional retina and tectum the symmetry with respect to orientation of the projection is continuous and more difficult to break. Therefore an additional mechanism, possibly involving chemical markers, is there to help fibres to find

![Fig. 4 The form of the potential $V$. Coordinates are $\xi$ and $\eta$, the amplitudes of the diagonal modes. There is a maximum at $\xi = \eta = 0$. For high values of $\xi$ and $\eta$ the potential rises sharply. There are two minima, on the axes, and a saddle - point, on the bisector.](image)
their approximate destination point on tectum, thereby breaking the orientation symmetry. It can be incorporated in the mathematical formulation discussed here in various ways, for instance by giving the α term a weak diagonal component.

8. Non-linear Interactions of Higher Order

The term \( w \cdot C(w) \) describes a positive feed-back of regions of elevated weights upon their own growth. The 8 term causes a competition within rows and columns. The existence of a diagonal of a broad profile therefore leads to growth along its crest and to suppression along its flanks. The profile consequently will contract and form a more precise retino-tectal projection, see fig. 5.

Fig. 5 Development of a sharp retino-tectal projection, controlled by a slowly decreasing α. Eventually a one-to-one projection results for \( α = 0 \) (not shown). The figure was produced by simulating equation (1) numerically.

This process can be expressed more formally in the language of sections 6 and 7. The existence of just one diagonal mode excites higher modes. This excitation is mediated by the quadratic term in (1), or more explicitly in (4). (The cubic term has only a damping effect.) The square of the fundamental mode has double frequency, the same orientation and the same phase. These two modes together excite a third mode, of triple frequency and still the same phase and orientation. In this way a chain of higher modes is excited, all of which coincide in phase and orientation. If the control parameter permits it, a diagonal with a very narrow profile will result. In [3] an explicit formula is given for the stationary amplitudes of all modes as a function of α.

The whole process of organization is controlled by an initially high and then slowly subsiding rate of unspecific contact formation α. When α is high, only the diagonal modes can grow, and they will compete. After only one of the orientations has survived, α slowly drops, more modes can grow, but they are tightly selected by the already existing modes. This proceeds to better and better resolution with only a few amplitudes in the process of decision at each time. If α had been very low right from the beginning, all \( N^2 \) modes of the system would have been unstable and a rather chaotic process of competition and cooperation between them would have ensued. The system could then have ended in another of the great number of possible stationary states (all permutation matrices are stationary if \( α = 0 \)).

9. Discussion

Ontogenesis of topological fibre projections, as treated in sections 4 to 8, is a very illustrative example, as it permits a rather elementary and explicit mathematical concretization of the general
traits of organizing systems as discussed in the first three sections: The system of cooperative interactions can in this case be formulated in an explicit and simple way as a system of differential equations with a simple intuitive interpretation. The elements of the next higher level of organization can be constructed explicitly in the form of a discrete set of modes of the linearized equation. This simplicity results from the assumption of periodic boundary conditions, by which small effects are avoided, that would be difficult to cope with theoretically. And it is possible to approximately derive the residual interactions between the principal modes, i.e., to formulate a second level of organization. The funneling-in of the system to the desired final structure through a sequence of progressively more detailed modes, discussed in the last paragraph, may be an important trait of many or even most processes of organization in biology. It seems that it imposes some geometrical or topological constraint on the structure of organizing systems.

In the last few years there have been many other applications of the synergetic scheme of organization to the nervous system, both to its development and to its function. Several of them are discussed and described in a unified way in the contribution of E. Bienenstock to this conference [5]. Also the relaxation method of artificial intelligence falls into this framework. I will devote the last section of this contribution to a short outline of a new approach to the function of the central nervous system, which was inspired by the principles of organization discussed so far. A more complete account of it is given in [6].

10. Hierarchically Structured Symbols

Almost all of current thinking about the function of the central nervous system is based on localization theory. It has been known for a long time that different parts of the brain are specialized to the processing of different subject matter (e.g., sensory or motor modalities). In the last decades electrophysiology was very successful in assigning specific bits of meaning even to single cells. Therefore the view prevails today that the cells in the brain play the role of 'atoms of meaning', and that the cells active within a particular fraction of a second additively compose the complex symbol which represents our state of mind in that moment.

This picture lacks one very important aspect which is present in all of man's cultural symbols: hierarchical structure. For instance, a book (as a high-level symbol) can be broken down into chapters, sections, paragraphs, phrases, words and letters (or ideograms). This is possible on the basis of geometrical grouping of letters. All types of evidence say that also the symbols of our mind are hierarchically structured. This is not to be confounded with the level of complexity of the meaning of single cells. Even if single cells represented grandmothers and cardinals, it would be necessary that they compose higher level symbols (e.g., descriptions of scenes) in a flexible way. Geometry, as in the text analogy, is not available to represent this hierarchical structure, because the cells don't move in our brain.

It is therefore proposed that the cells can dynamically express grouping into blocks, etc., by synchronizing their activity in time (with a resolution of a few milliseconds). A complex symbol needs for its expression a time interval of several hundred milliseconds. Two part-symbols (e.g., active cells) can cooperate to excite a third place only if they are bound to each other (i.e., their cells
synchronized with each other); this is a natural consequence of the non-linearity of neurones, hence of their coincidence detector property.

Synchronizations are a natural consequence of the existence of excitatory connections between cells. However, symbol formation must be a dynamical process; two lower level symbols may be bound in one moment, separate in another. It therefore is necessary to postulate that the excitatory connections change dynamically in their effectiveness, on a time scale of fractions of a second. The effectiveness of a connection between two cells is increased from a resting value if the activity of the two cells is synchronized in time. Conversely, lack of synchrony temporarily renders the connection ineffective. In the absence of activity connections slowly fall back into their resting state, with the time constant of short-term memory.

The positive feedback between effectiveness of connections and synchrony of signals is the basis of an organization process. Short alternative paths between two cells cooperate with each other in synchronizing activity of a target cell with a source cell, and consequently in growing in effectiveness (compare fig. 1). Nets are thinned out by the action of an inhibitory system which suppresses global synchrony. Organized structures are therefore thin graphs with a maximum of cooperation between surviving connections. It may be conjectured that an organized net has a topological structure in the sense that the cells of the net can be arranged in an appropriate space such that the surviving connections link closely neighbouring cells. Note that the topological projections of sections 4 to 9 are of this type. Arguments are given in [6] that fast organization processes on the basis of cellular synchronizations and rapid temporary changes of connection structure lead to a solution of such important problems as figure-ground separation, combinatoric build-up of feature detectors of high level from those of low level, and the invariance problem of perception.

References


