

Space-time Relations in Wave Interference Systems with Attention to Nerve Networks

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Abstract

The role of the paper¹⁾ is to discuss the relevance of physical wave properties to nervous systems. Time-functions propagate very slowly, while wavelengths (product of pulse duration and propagation velocity) are very short. Any questions of information processing (where do the data come from, where do they go to, what is their content) seems to be closely coupled to interference locations. We will discuss new dynamic, basic functions of neural circuits in space and time. Simple physical models generate interesting behaviour: *mirroring projections, moving, zooming, overflow*. With the help of some simulation experiments with time-functions in space we will give some impressions about possible properties of neural assemblies. We introduce an informational role for nerve delays, wiring shapes, velocities, waveforms and channel numbers into a new field '*Wave Interference Informatics*' and show, that the role of *delays* is as important as synaptic *weights*.

Introduction

The paper carries the following assumptions:

- a) A wire in nerve system has a limited velocity. It acts like a *wave conductor* with length to diameter dependend delay, not like an electrical node.
- b) We will avoid the usage of state-machine models with intermittend timesteps (McCulloch/Pitts 1943).
- c) Short impulses and low velocities produce geometrical puls lengths in the range of μm to cm. To calculate *meeting points* of pulses we will calculate the nerve system in spatial, 3-dimensional representations.
- d) While the possibility to excite a place is as much higher, as much closed *in time* different waves or impulses from different directions appear, we will ask for locations of superimposition or interference.
- e) Any nerve cell body has a non-zero size. Where here is one cell body, there is not another. Thus, any signal flow bridges distances and needs (incremental small) *delay time to reach any destination*.
- f) Following Hodgkin/Huxley, nerve velocity is influenced by background (glia) potential. Thus interference locations are influenced too. We will observe properties of

this special case (zooming, moving).

g) Like a tree a nerve branches out. Thus (ionic, molecular or cellular) information carriers, which we shall call 'impulses', split at possible places into very different directions and they meet again at other places.

h) Whether we consider the flow of chemical substances (e.g. leucin, acetylcholesterase, mitochondrial containers etc.) through nerves, or ionic mechanisms (Na^+ , K^+), or the measurable electric representation of some transportation mechanisms (Fig.1a), the nervous system can be seen as a system of different channels or an inhomogenous system of wires in real space dimensions and with real signal delays between computational nodes carrying different signals with different velocities (*colored flow graph* [6]). Gates stop or modify the information flow at certain places (i.e. at synapses). Each mechanism carries a time function with a certain velocity and a certain flow direction. Because different mechanisms work together, different signal carrier types ('colors') flow with different velocities on a nerve. Independently of their type, signals can only go discrete ways, they only can flow through nerves.

i) Neurons without axons, dendrite to dendrite or axon to axon coupling between nerves (Crick/Asanuma) suggest the idea of nerve system as inhomogeneous wave space (neuropile) with soft synaptical influence only.

By conceiving physical networks with velocities, distances and delays however small we discover new classes of code-, frequency- and location-sensitive networks called '*interference networks*' working in 4-dimensional (x,y,z,t) wave spaces. As a special characteristics, pattern carrying interference networks mirror the input-output direction. By analogy with optical projections we shall call this behaviour '*projective*'.

We will find, that circuits of general attention in neurocomputation mostly seem not to work in wave space environment (for example unsymmetrical nets like the net for concept formation, Amari 1977).

Time functions in space, characteristic delay vector of a location

Supposed that different impulses move within a

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dendritic tree to any neural soma from different directions with a low velocity. Suppose further, that a neural cell body receives waves from n different sources. The time function $g(t)$ of n delayed time functions f_k that are able to excite the neuron is in time t and at location $P(x_0, y_0, z_0)$ with interference function Ψ (sum, product...)

$$(1) \quad g(t) = \Psi \sum_{k=1}^n f_k(t - \tau_k); \quad k = 1 \dots n; \quad \Psi = \Sigma, \Pi, \dots$$

The **effective value** g_{eff} of the **interference integral** of $g(t)$ in the time interval T (pay attention to the positive time axis direction for an inverse delay vector) may be

$$(2) \quad g_{\text{eff}} = \sqrt{\frac{1}{T} \int_{-T/2}^{T/2} g^2(t) dt},$$

Note, that times and delays are not to be regarded as integer values, as introduced by McCulloch/Pitts 1943. For **inhomogeneous spaces** (nerve cell assemblies) an exact measurement or modelling of delays τ_k is necessary.

For **homogeneous delaying spaces** there exists a well known correspondence between distance s (dx, dy, dz), velocity v and delay τ_k

$$(3) \quad \tau_k = \frac{1}{v} \sqrt{(x - x_0)^2 + (y - y_0)^2 + (z - z_0)^2}$$

Any tree at the cell body P has a **characteristic delay vector** M ('mask') of wiring delays in relation to points K_i ,

$$(4) \quad M = \{\tau_1, \tau_2, \dots, \tau_n\}^T$$

where n is the channel number. Observing generating and receiving points P we find, the characteristic vector M^* of the location P of a *receiving tree* is the inverse vector M^* of wiring delays M of a *generating tree* because

$$(5) \quad M^* + M = \tau\{1\}$$

$$(6) \quad M^* = \tau\{1\} - M$$

where $\{1\}$ is the unity vector and τ is the total delay of an arrangement, see Fig.4. The interference integral (the possibility to be excited) becomes maximum, if pulses over different partial paths between sending and receiving points reach the destination simultaneous.

Because the total delay mostly has no role, it is possible to simplify the equation sometimes to $M^* = -M$.

If the space dimension D is in relation to the channel number n , we call the system '**well conditioned**'

$$(7) \quad D = n - 1$$

Observing inhomogeneous space geometries, D defines the dimension of an equivalent, homogeneous problem solving space.

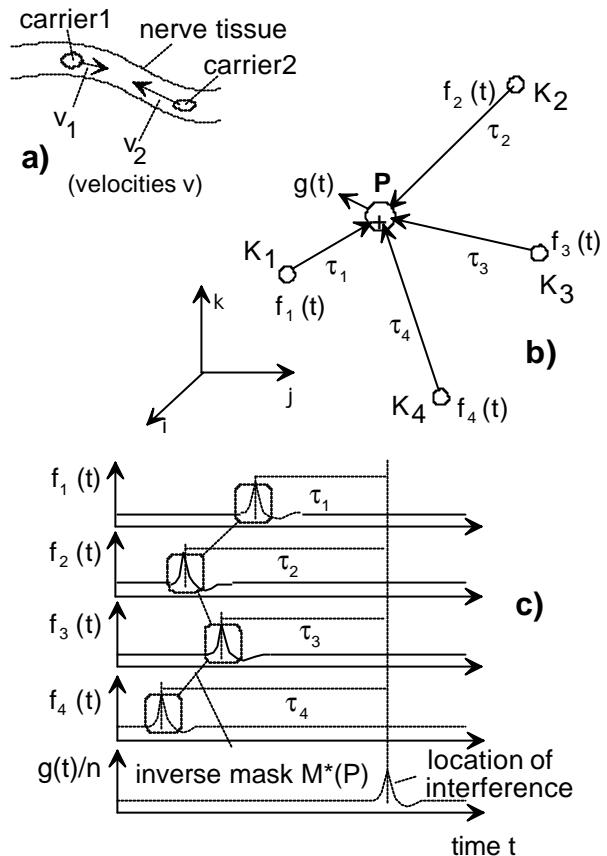


Fig. 1: a) Colored interference system, nerve tissue with two carrier types; b) time function $g(t)$ of point P summing up four sources $f_k(t)$; all wires imply distributed delays; c) maximum interference in P occurs if functions $f_k(t)$ appear pre-delayed with the inverse delay vector $M^*(P)$

Dynamic basic functions of neural trees; burst generation and -detection

Suppose two neurons coupled with its fibre trees, Fig.2c). We get a substitute circuit Fig. 2d). We suppose an input time function $x(t)$, unity weights $w_k = 1$ and a summation point creating an summative output $y(t)$

$$(8) \quad y(t) = \theta(w_i x(t - \tau_i) + w_j x(t - \tau_j) + \dots + b)$$

Depending on a bias b and a threshold function θ , the neuron has different possible answers to any input.

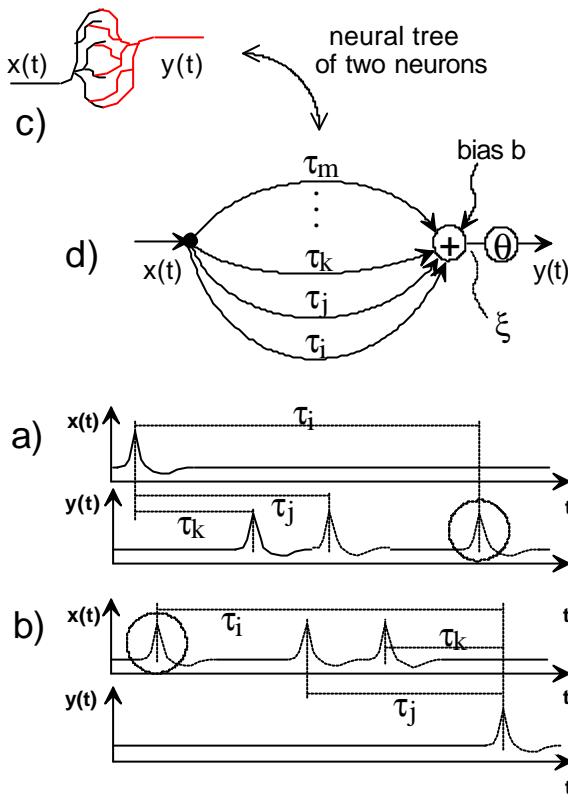


Fig. 2: Equivalence circuit d) of a coupling c) of neural trees acting as a) code or burst generator; b) code or burst detector

Some special cases may be of interest. We use normalized time functions and weights. A simple, ramp-like threshold function $\theta(\xi)$ is used in the range 0 to 1 with $\theta'(\xi)/d\xi = 1$, (see Fig. 2e).

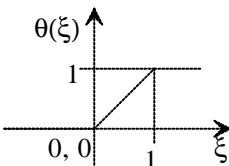


Fig. 2e

a) In the case of a large bias (boolean OR-type) each single input impulse appears delayed at the output. So we call this case **burst generation** or code generation, Fig.2a and Fig.3a.

b) Using a small bias near the inverse sum of weights $g_i(t)$ (boolean AND-type) all inputs of the adder have to have the level 'one' to reach any output. This case is called code or **burst detection**, Fig. 2b, 3b.

c) For a bias of zero, with a sum of weights near one and small delay differences, the circuit produces floating or **gating potentials**, Fig. 3c.

d) If the receiving mask differs from the incoming burst, according to Fig.2b) the neuron is almost not excitable, the

mask acts like a key. We call this case **dynamic inhibition** or delay vector inhibition (for example see Fig. 2a, 2b).

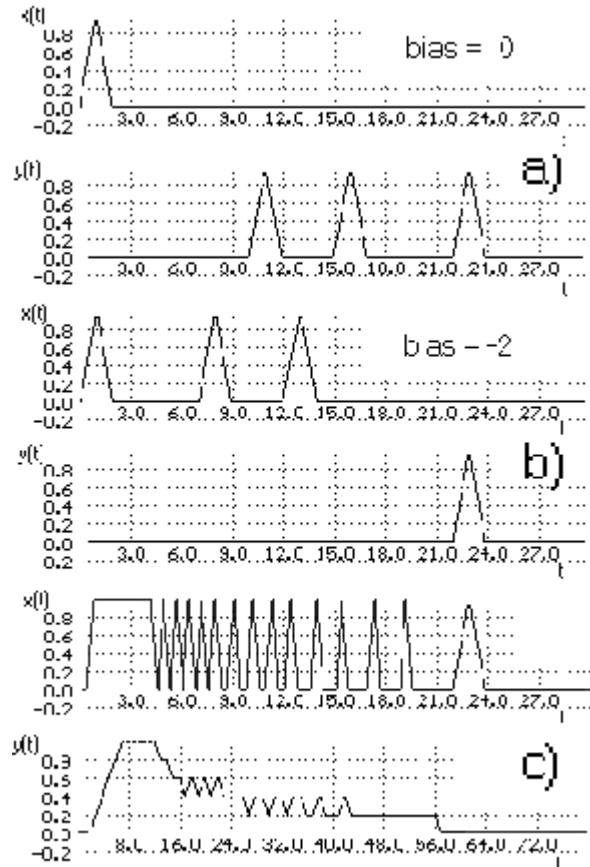


Fig. 3: Testing dynamic basic functions²⁾ of a tree coupling of two neurons (example). a) code generation: weights $g_1 \dots g_3 = 1$, bias = 0, delays = 10, 15, 22 samples; b) code detection with inversive delay vector: similar to case a) but with bias = -2; c) gating potential: six inputs, all weights = 0.2; delays = 1, 2, 3, 4, 5, 6; bias = 0, (x-axis incompletely drawn)

A special case of rule d) is that of **dynamic neighbourhood inhibition**. Suppose two symmetric, connected neuron trees 1 and 2. Both neurons may have an identical geometry with $M = M_1 = M_2^*$. For interference maximum, the delay vectors have to fulfil $M_1 + M_2^* = t\{1\}$; $2M = t\{1\}$; $M = t/2\{1\}$. So the firing of one neuron can excite the other only if all places of coupling (i.e. synapses) have the same delay radius around the cell soma.

Two neuropiles connected via some axons

Cortical neurons have on average thousands of synapses. Neural space seems to be full of short circuits.

²⁾ Experiments with dynamic simulator 'Neuronet', Oct. 19-20, 1994; development: G. Schoel, P. Puschmann, FHTW Berlin

Suppose we have two neural assemblies connected via some axons or pulse transmitting channels, Fig. 4. The one neuropile may generate some impulses, waves interfere in the other. For simplicity, neural spaces may have delays proportional to distances in space (partial homogeneous spaces). All delays t_{ij} , t_j , t_{jk} may depend on distances only, $i = 1 \dots m$ (firing neurons), $j = 1 \dots n$ (channel number), $k = 1 \dots p$ (detecting neurons).

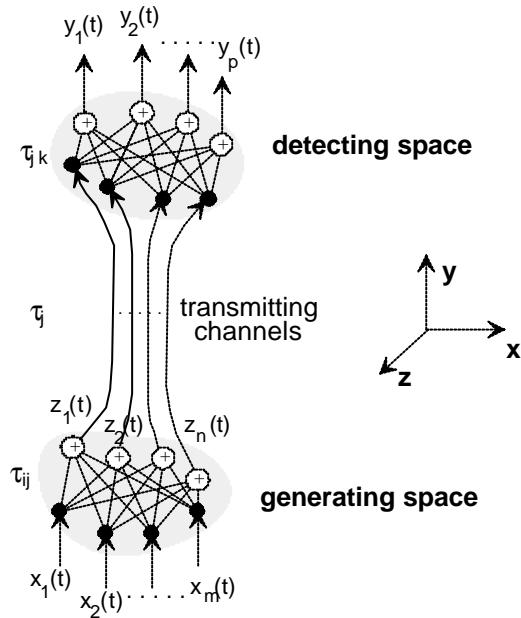


Fig. 4: Two neuropiles connected via some axons as a basic interference circuit (all wires have wave properties with limited velocities)

A signal crossing this circuit runs along all the different paths. Points of high interference are located in the opposite space, in contrast to **non-mirroring, synaptic projections** wave circuits of this type produce **mirroring projections** (comparable to optical projections). The higher the multiple self correlation of a signal is, the higher is the effective value of the interference integral. It seems to be of some interest, that while *transmitting channels* can have *high velocities* or delays near zero, *field velocities* have by contrast to be *very slow* for sharp interference locations. Note, that the *slower* the neuropile, the *sharper* is the interference location. In the most of following simulations delays of transmitting channels are supposed to be equal and zero.

Only transmitting channels (Fig.4) can have zero delays. But the model become worthless, if the velocities within the generating and the detecting neuropiles become infinite. In fact we can find long myelinated axons

to decrease reaction times, but myelinisation of neuropiles is not known. Also the model would become worthless if generator/detector velocities become infinite.

Observing the circuit, it seems to be comparable to neuroscience's synaptic circuits. What is the difference? Supposing *equal* synaptic weights, any such circuit is not able to transmit information without waves. Using pulses it works inverted. Now it can *only* produce **mirrored** projections instead of the **non-mirrored** projections of the synaptic type.

Different properties of this circuit have been studied^{3]} by the author between 1992 and 1998. Because there is a bad chance to get analytical solutions for wave spaces, a special software PSI-Tools (PSI: Parallel and Serial Interference) was developed to calculate the wave fields. It uses the so called *H-Interference Transformation* (HIT) as basic algorithm [6].

Interference-projection via -reconstruction, overconditioning

Two tasks are of interest for the interpretation of time functions flowing through the transmitting axons (channel data stream):

- a) For technical purposes, the (non-mirroring) **reconstruction** of the excitement of a generating field is of interest. It can be realized by a propagation of the time-functions back to the generating space.
- b) In nerve-simulations also the (mirroring) **projection**, the excitement of a detector field is of interest.

From a physical viewpoint, *reconstruction and projection are two sides of one coin*. Using comparable spherical coordinates only, the **time direction** of channel data stream decides between them (Fig. 5c, 5d). Neural *projections* share the same problems as optical projections: depending on the degree of over-conditioning (channel number versus space dimension), interferences decline the more one moves away from the central axis^{4]}. Any *reconstruction* (Fig.5c) reasoned by perfect delay compensation reproduces the generators excitement scheme without distortion and over-conditioning problems in general. On the other hand, the *projection* in Fig.5d), over-conditioned by one channel, do not reproduce the excitement scheme. While for example three channels reproduce all self interferences in 2D-space, higher channel numbers progressively suppress cross interference points.

Parameters of pulse-interference systems

The **geometrical pulse width** l determines the sharpness of a pulse projection, it is defined by peak time

^{3]} http://www.gfai.de/www_open/perspg/heinz.htm

^{4]} http://www.gfai.de/www_open/perspg/g_heinz/pressinf/bilder_d.htm

t_{peak} and velocity v

$$(9) \quad I = t_{peak} v.$$

Cross interferences can occur, if a next wave $i+1$ comes into a field, while a wave i has not lost the field. A smooth indicator is the *cross interference distance* d with an average pulse distance t_{pulse} ('refractory period')

$$(10) \quad d = t_{pulse} v.$$

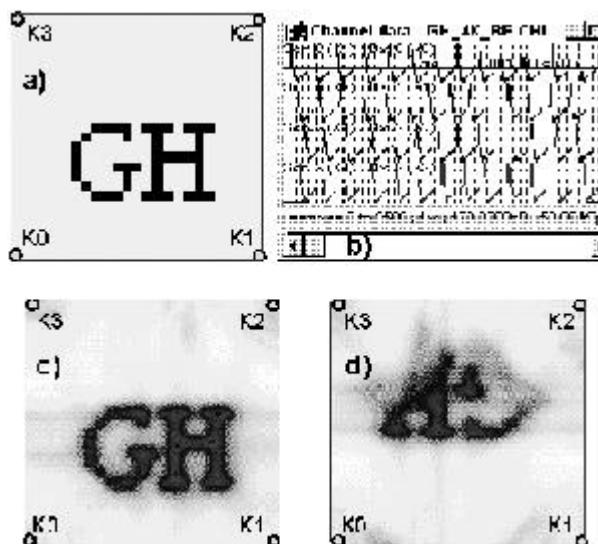
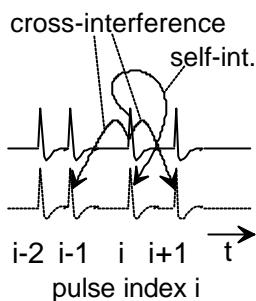


Fig. 5: Reconstruction and projection at the interference circuit of Fig. 4, over-conditioning system ($n = 4, D = 2$). From left to right:

a) generating field with firing neurons as black pixels (channel origins K0...K3); b) channel data stream (four channels); c) reconstruction of the generating field with time-reversed channel data; d) projection into the detecting field
(source: Heinz 1994; 1996)

Data: field sizes 9 x 9 mm; velocity $v = 3000$ mm/s; average pulse distance 3 ms ~ 9 mm; time function length 80 ms; geom. pulse width = 0.1 ms ~ 0.3 mm; generator and detector field are set to identical coordinates.

It acts as the radius d between any interference location and a possible next interference location. Neurons fire one after the other depending on the pause. Channels are located at drawn positions with starting points in the generating layer and with end points in the detecting layer.

Cross-interference overflow

Fig.6 shows the dependence of interference on pulse distance. To avoid cross interferences in general, the larger is the space dimension, the greater should be the cross interference distance, see Fig.6. To get detailed projections without *over- and under-conditioning* effects, there is an optimum number of channels n related to the wave space dimension D , with $n = D+1$.

Example: For an average pulse distance (refractoriness) of 20 ms and an detector velocity of 0,5 m/s what is the maximum radius of the self interference space? With a cross interference distance $d = t_{pulse} v$ it is approximately 10 mm. This is the **maximum region of topologic projections without cross interference pattern** (Lashley's holographic memory) and without self-holography (see also 'moving projections', case g with $v = 10$).

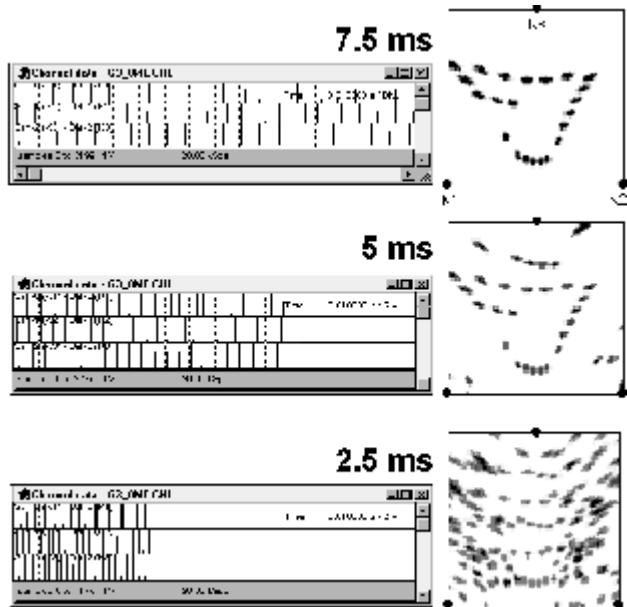


Fig. 6: Cross-interference overflow (pain?) as a function of three different firing rates/pulse distances (average in milliseconds). Firing neurons of the generator arranged in form of the character 'G'; three channels feed the fields (K1, K2, K3)

Data: pulse distance variation 7.5 to 2.5 ms; field size 1x1 mm; velocity 200 mm/s; pulse peak ca. 0.1 ms ~ 20 μm; cross interference distance varies between 1.5 and 0.5 mm, channel feeding points located on the detecting field

The suppression of cross-interference improves as more channels are used. By contrast, interference circuits with low channel numbers only work, when time functions are spike-like. Nevertheless over-conditioning effects increase as more channels are used.

In some situations the cross-interference distance becomes unbalanced, for example in the case of injuries.

Generating neurons begin to fire with very high rates. Cross interference distances shrink, see Fig. 6. When the density of generating impulses is increased, more and more cross interferences appear in the detecting field. From a physical point of view this could be classed as "pain"^{5]}.

Projection quality depending on distance

Is the relative distance between sensing and sourcing points relevant for a projection? To answer the question, we tried further experiments, Fig. 7. Varying the distance ' a ' between source points and the field produces different projection qualities. While short distances promote cross interference, large distances destroy the image.

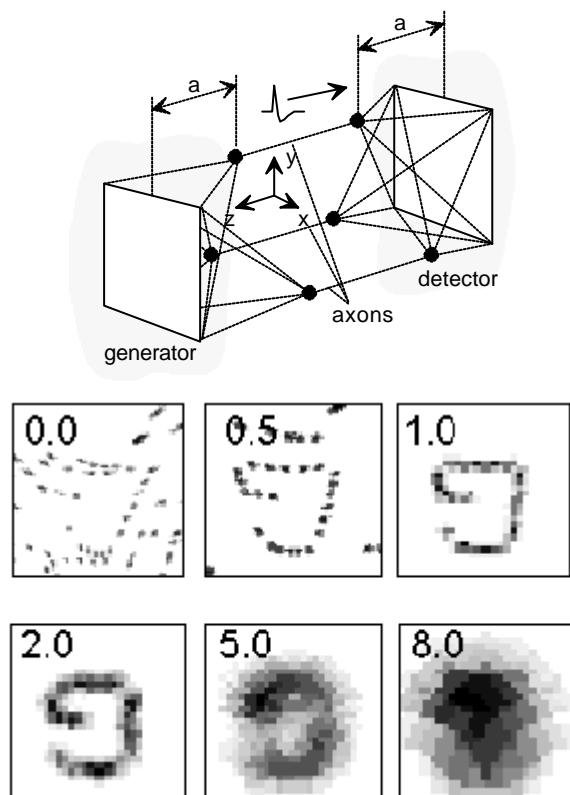


Fig. 7: Variation of the distance a between feeding points and fields. We find different projection qualities. Parameter is a in mm (Heinz 1996)

Data: field size 1x1 mm, velocity 200 mm/s; pulse peak ca. 0.1 ms ~ 20 μ m; average pulse distance 4 ms, cross-int. dist. ~0.8 mm

Topomorphic overlayed projections

In our imagination it is possible, to overlay images or impressions without problems. Are there theoretical grounds for such behaviour? To test this, we overlay two channel data streams.

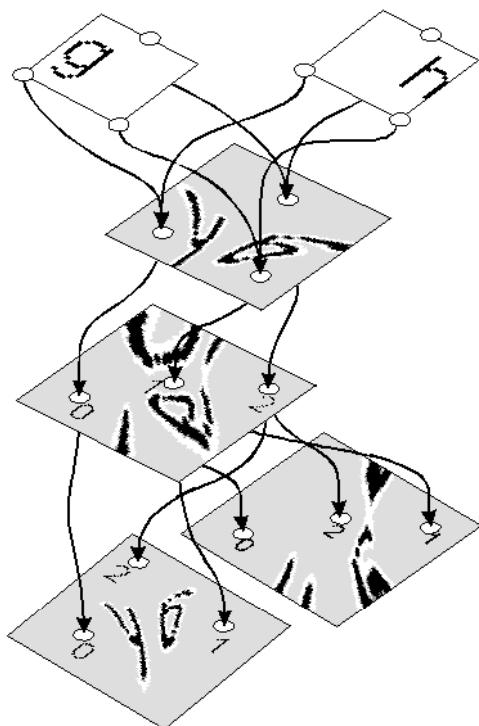


Fig. 8: Overlay of two fields. Topomorphic projections with different channel source points⁶. Channelwise overlay (addition) of two 3-channel data streams, generated from independent source fields 'g' and 'h' (simulation with PSI-Tools, source: Heinz, 1996)

We suppose, that all channels have the same channel number and project into a comparable space or field. Using two generator fields, the firing neurons are arranged in the form of an 'g' in the first and in the form of an 'h' in the second. We add or append the generated time functions sample by sample and channel by channel. Projections into different detector fields show, Fig. 8, that both generator images have been combined. If channel source points are moved in the detector field, the projections become distorted. But the projections of 'g' and 'h' maintain in a **topomorphic relation**. It is not possible to separate them.

Moving projection by channel delay

In our mind, imagination suggests images as the

^{5]} see also http://www.gfai.de/www_open/perspg/g_heinz/sim/pain/pain.htm

^{6]} see also http://www.gfai.de/www_open/perspg/g_heinz/pressinf/bilder_d.htm

word itself confirms. Our brain seems to work with the natural world of images, movement and sound. Abstract thinking with numbers, for example, appears as a hard task, if one tries to do it without the help of imagination. Up till now, we did not know a technical systems able to produce floating images or movies without of the use of picture-series.

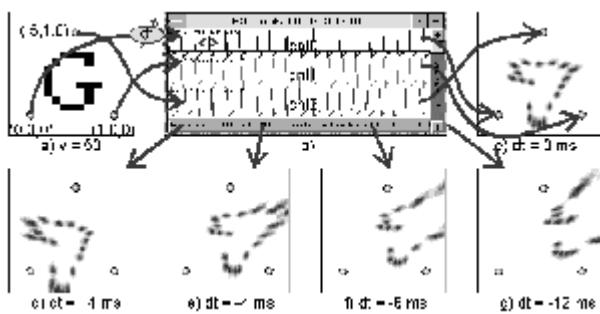


Fig. 9: Moving projection produced by a single, delaying axon in chl0. a) generator field; b) generated time functions; c)...g) detector field; c) no channel delayed; d) K0 delayed by 4 ms; e)...g) negatively delayed (source: Heinz 1996)

Suppose that one channel is delayed by a parametric change dt of any connecting axon between generator and detector field. Then the interference locations change in such a way that impulses meet each other at shifting places, Fig. 9. So, images become 'floating' according to an amount of a single channel delay variation!

Zooming projection by field velocity

Over large areas of cortex one can measure weak glia-potentials, known as the EEG or ECoG. Already in the Hodgkin/Huxley model any volume potential change varies the propagation velocity of a neural path.

Let us suppose, that the background velocity changes within all neurons in the detector space influenced by such a glia-potential.

We find, that velocity changes v in the detecting field, for example reasoned by the influence of glia, have a zooming effect on the projection, Fig. 10.

From this viewpoint it seems, EEG/ECoG-probes can be interpreted as measurements of zooming/moving control potentials only, reproducing a mathematical difference between a memorised code, image or function and a projection of any real input.

The 'Neural Hologram' (Lashley 1950, Pribram 1974)

Lashley studied the formation of memory by lesioning various parts of rat brains. Large areas could be removed, but animals were still able to reproduce the learned behaviour. In the section 'cross interference distance' we discussed and in Fig.10g) we demonstrate a comparable behaviour. In case of low velocities v or large field areas, waves come into cross interference within the field, because the *cross interference distance* will become smaller as the field size. Wave i interferes with followers $i+k$ and with previous waves $i-k$ of the other channels. A kind of 'holographic' projection (better: *cross-interference projection*) happens with reference waves coming from the other channels.

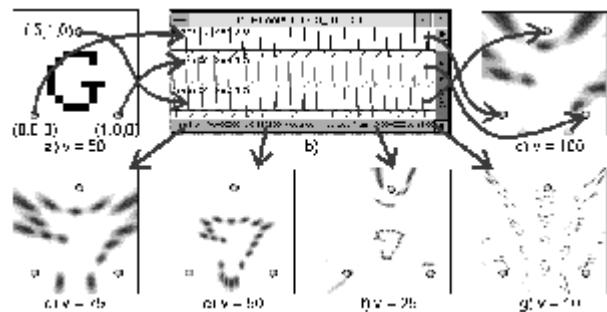


Fig. 10: Zooming and cross-interference replication produced by varying field velocities. a) generator field; b) channel data stream; c) and d) increasing sizes for higher velocities; e) projection with original field velocity $v = 50$; f) and g) reduced sizes for low velocities: cross-interferences in g) appear self-replicative (source: Heinz 1996)

Data: field size 1x1 (cm); vgen = 50 cm/s; vdet = 10...50...100 cm/s; average pulse width 1ms; pulse wavelength 0.1...0.5...1 mm; average pulse distance 20 ms ~ 2...10...20 mm; 10 kS/s

We will call this general behaviour of interference systems *self-holographic*. Because every impulse has following and preceding pulses or waves, interference systems can be seen as self-holographic in general if delays between sourcing points are higher the pulse-distances.

Burst as neural address, sender-receiver relations

Let us return to the basic functions of a neuron. We have seen, that coupling trees are able to produce a burst. To reproduce a single impulse at a neurons output it is necessary, to use the inverse characteristic delay vector, the 'mask'. Detection is possible if the tree uses the

complementary mask. Suppose different trees, we find, that each neuron on the left side (Fig. 11) communicates *only* with special trees on the right side. In the example, masks M_x and M_x^* are inverted. The neuron with mask M_1 communicates with M_1^* , M_2 with M_2^* and M_3 with M_3^* . So bursts can be seen as (parallel or serial) neural addresses, allowing any communication between different neuron trees across a (single or multiple) axonal path. It may be of some interest that this kind of communication can work in both directions. Theoretically neurons this way can talk bi-directionally if the bias can be modified.

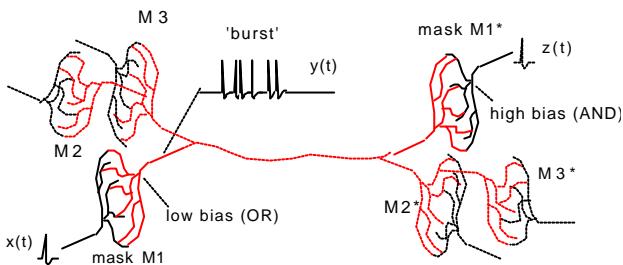


Fig. 11: Bursts can be seen as neural addresses to transmit different data streams on single axons (equivalence circuit see Fig. 2)

The *burst* acts vice versa: it encodes both the *sender address* and it also encodes the *address of the receiver*. It is not possible to break this relation. Both addresses depend only on a single sign: the *direction of the time axis*. Supposed we have the 3-dim. nerve graph, if the time flows *forward*, we get the *projection*, the receiver address. If the time flows *backwards*, we get the *reconstruction* and the sender address or location - all with the same channel data stream!

Conclusions

As an alternative to the well known McCulloch/Pitts approach we investigated the role played by delays coupled to nerve lengths and distances in physical wave spaces.

We studied pulse interference projections between two short-circuit neuro-piles avoiding the use of synaptic weights. The parameters varied were delays, velocities of pulses, pulse duration, pulse distance and coordinates of feeding and sensing points in spatial arrangements.

Introducing the characteristic delay vector (mask) of a location we find *new dynamic basic functions* of neuron connections or neural trees.

We find *mirroring projections* in a detecting field and *non-mirroring reconstructions* on the generating field. The only difference between projection and reconstruction is the *time-flow direction* of the time functions (channel data).

One of our experimental arrangements consists of two short-circuit subspaces connected via some wires (axons). On changing the field velocity, projections begin to *zoom*. For small channel numbers we find *cross-interference replication* in simulation, supposed by Lashley in 1949. Modifying axonal delays, projections move across the detecting field.

For the calculation of interference locations the velocity diagram of a neuropile is important to know.

Projections can be overlayed and *remain topomorphic*. Moving the axonal source points over the field, projections become distorted but remain topomorphic. Because every impulse has following and preceding waves, interference systems can be seen as self-holographic in general.

Fast firing into a field we find increasing cross-interference overflow, implying *pain-like behaviour*. Varying the distance between axons and field changes the *projection quality*.

Interference circuits can help to analyze the role of *myelinization of long axons* and slow neuro-pile velocities in combination. While animals in biologic evolution need short reaction times to improve their chance of survival, pulse-propagating nets need the opposite: neural communication, data addressing and information processing couples to a slow flow of information in interference regions, resulting in small geometrical pulse-widths. Only the connecting channels between generator and detector spaces (axons) can be infinitely fast without influencing the information processing. In fact we also find axons with myelin-insulation that propagate pulses at highest velocities over long distances.

Physical network simulations of simple neural assemblies can reproduce different known, higher brain functions, in particular an *image-like information processing* on uncertain, inhomogeneous but uniform neural subspaces.

If neural delays and codes depend on space distances, neural functions are *coded by locations* in space and thus *by the geometry of the neural tissue* independent of weights and thresholds. Space-dependent delays appear as the 'coding institution', the code is the location, space codes the timing and so the neural tissue dominates the coding of the behaviour.

Bursts appear as neural data addresses. Different neurons can communicate over single axons.

Over-conditioning problems appear if the channel number is greater than the space dimension plus one. Interference locations become indifferent for high channel numbers in homogeneous space. Using inhomogeneous, wired interference spaces over-conditioning disappears. Because nerve fibres have different velocities and chaotic connectivity schemes, neural delay space can be regarded

as higher dimensional.

If we compare static, synaptic and dynamic, wave interference aspects, any multi-channel, neural network tends from the static, synaptic behaviour to a *non-mirroring* data transmission, from the dynamic or wave interference aspect to a *mirroring* data transmission.

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