Understanding Brains Through Experiments and Models of Neurodynamics

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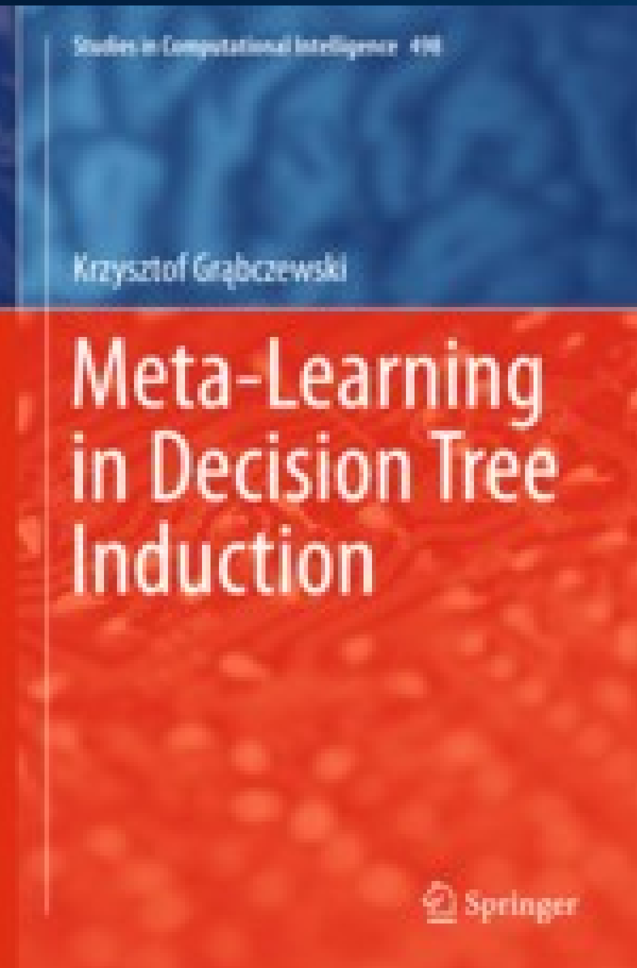
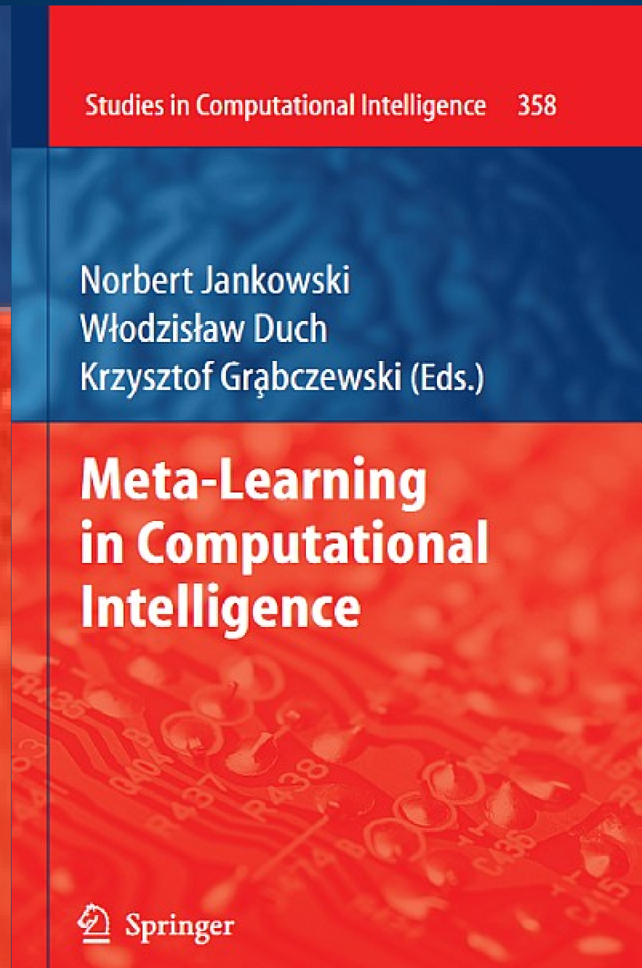
ICAISC, Zakopane, 12-16.06.16

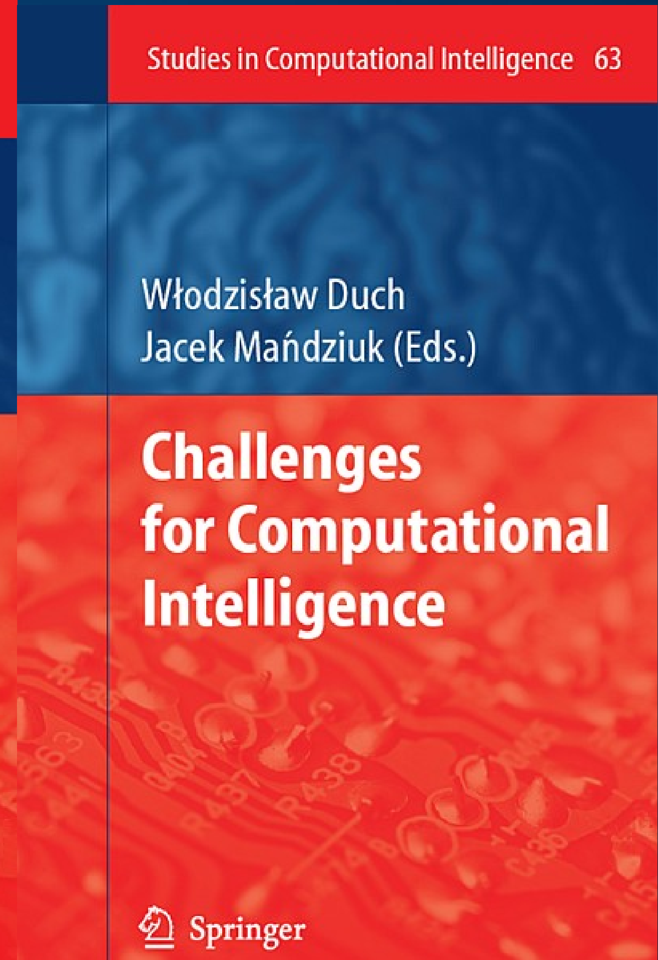
DI NCU Projects: CI

Computational intelligence (CI), main themes:

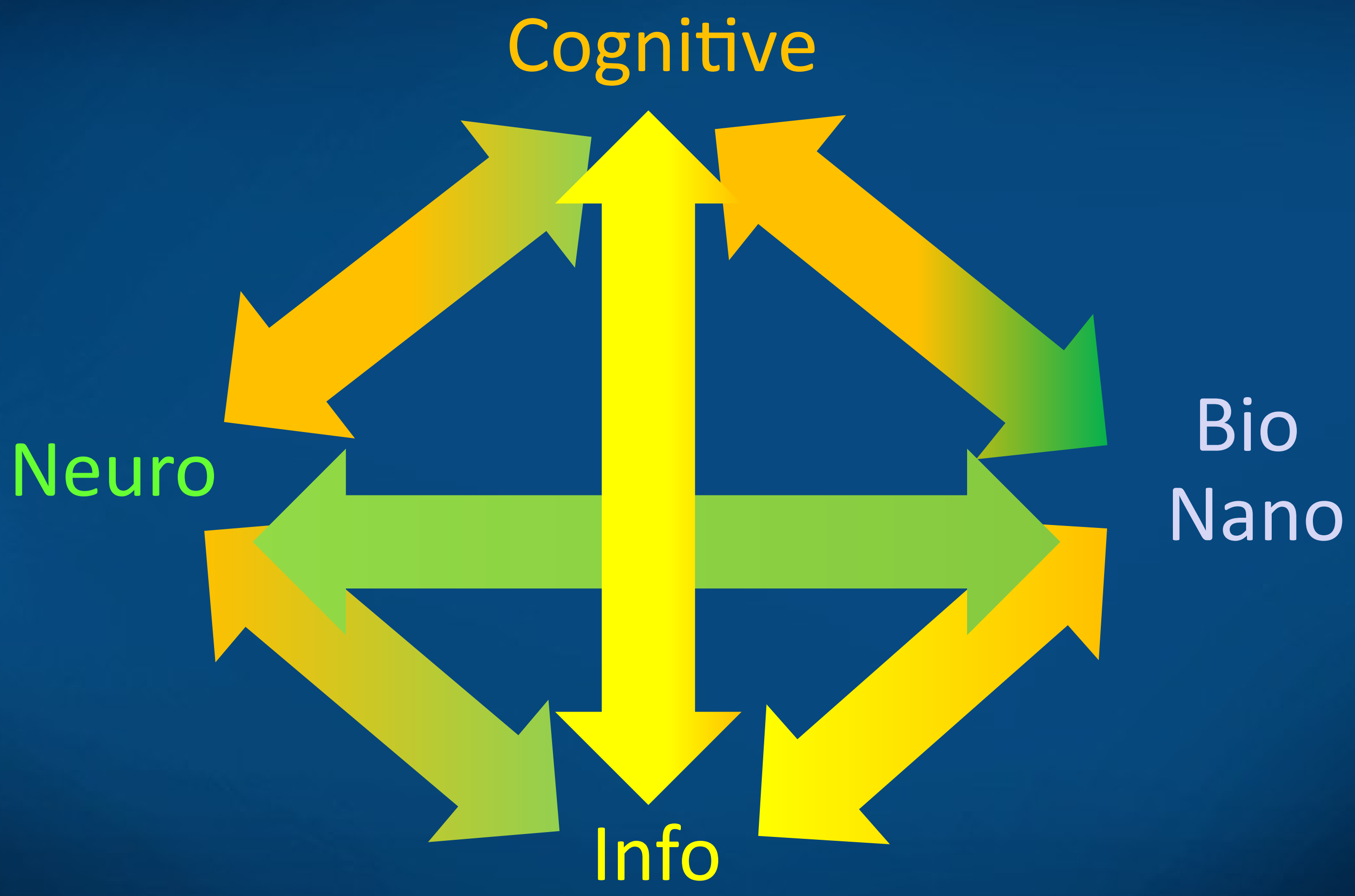
- Foundations of computational intelligence: meta-learning, transformation based learning, k-separability, learning hard boole'an problems.
- Novel learning: projection pursuit networks, QPC (Quality of Projected Clusters), search-based neural training, Universal Learning Machines for transfer learning/learning from others (ULM), Support Feature Machines (SFM), almost Random Projection Machines (aRPM), and more ...
- Understanding of data: prototype-based rules, visualization of NN function and visualization of dynamic trajectories.
- Similarity based framework for metalearning, heterogeneous systems, new transfer functions for neural networks.
- Feature selection, extraction, creation of enhanced spaces.
- General meta-learning, or learning how to learn, deep learning.


Studies in Computational Intelligence
Krzysztof Grąbczewski
Meta-Learning in Decision Tree Induction
Springer


Studies in Computational Intelligence 358
Norbert Jankowski
Włodzisław Duch
Krzysztof Grąbczewski (Eds.)
Meta-Learning in Computational Intelligence
Springer


Studies in Computational Intelligence 63
Włodzisław Duch
Jacek Mańdziuk (Eds.)
Challenges for Computational Intelligence
Springer

Most important 21 century technologies



Ultimate technology: NeuroCognitive Informatics in Nano-hardware.
Today - more science than math or engineering.

Center of Modern Interdisciplinary Technologies

Why am I interested in this?

Bio + Neuro + Cog Sci + Physics =

Neurocognitive lab.

5 units with many projects requiring experimental work.

Main theme: maximizing human potential.
Pushing the limits of brain plasticity and understanding brain-mind relations, with a lot of help from computational intelligence!
Funding: national/EU grants.

A group of neurofanatics

Our toys


personal genome machine


Treatment Coil
Prefrontal Cortex
Stimulated Area
Magnetic Field
NEUROSTAR

DI NCU Projects:NCI

Neurocognitive Informatics: understanding complex cognition
=> creating algorithms that work in similar way.

- Computational creativity, insight, intuition, imagery.
- Imagery agnosia, especially imagery amusia.
- Neurocognitive approach to language, word games.
- Medical information retrieval, analysis, visualization.
- Comprehensive theory of autism, ADHD, phenomics.
- Visualization of high-D trajectories, EEG signals, neurofeedback.
- Brain stem models & consciousness in artificial systems.
- Geometric theory of brain-mind processes.
- Infants: observation, guided development.
- Neural determinism, free will & social consequences.

Phenomics

Phenomics is the branch of science concerned with identification and description of measurable physical, biochemical and psychological traits of organisms.
Genom, proteom, interactom, exposome, virusom , connectom …
omics.org has a list of over 400 various *…omics* !

Human Genome Project, since 1990.
Human Epigenome Project, since 2003.
Human Connectome Project, since 2009.
Developing Human Connectome Project, UK 2013 + many others.

Behavior, personality, cognitive abilities <= phenotypes at all levels.
Still many white spots on maps of various phenomes.

Can neurocognitive phenomics be developed to understand general behavior of people? Where should we start?

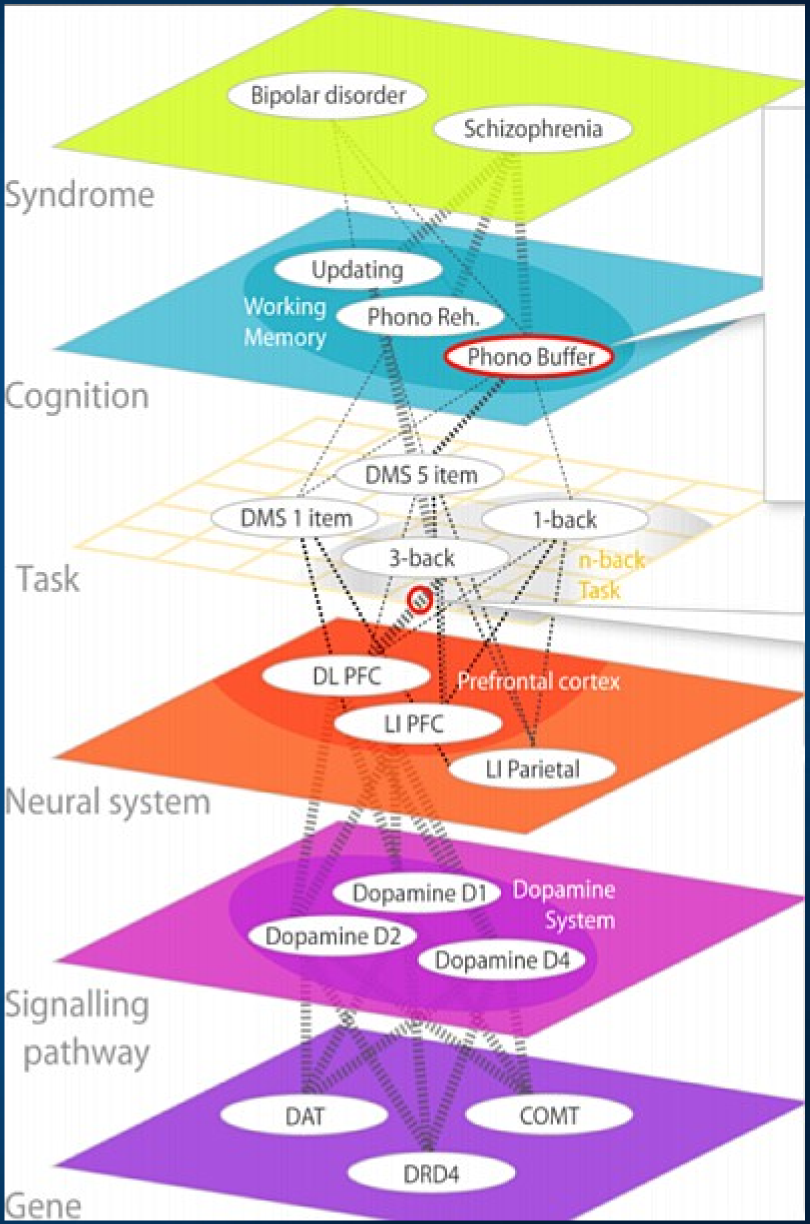
Neuropsychiatric Phenomics in 6 Levels

Consortium for Neuropsychiatric Phenomics (CNP)/NIMH RoDC approach:

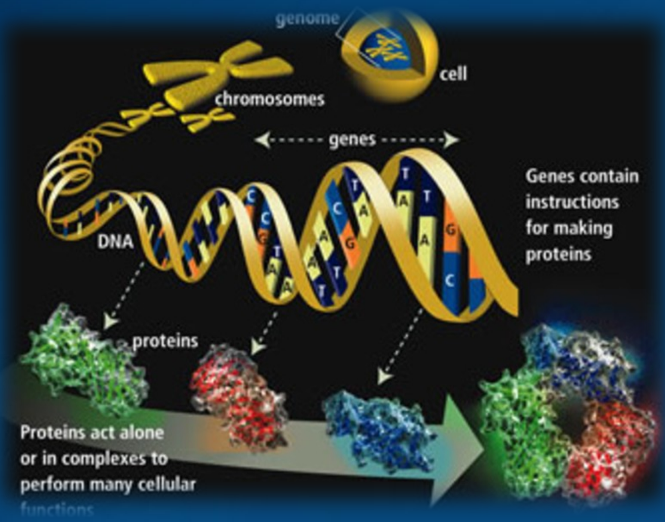
Research Domain Criteria (RoDC) analyzes large brain systems – negative/positive valence systems, arousal, cognitive, affective systems – through interaction of Genes, Molecules, Cells, Circuits, Physiology, Behavior, Self-Report, and Research Paradigms.

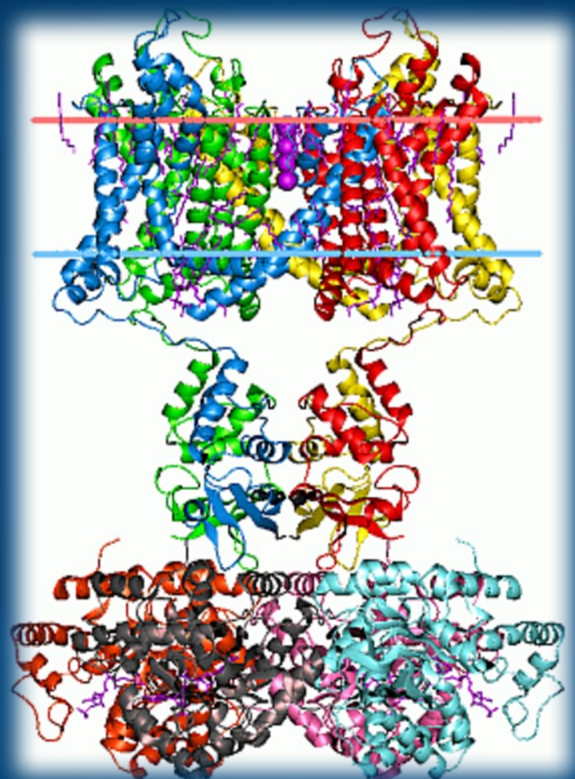
From genes to cognitive subsystems and behavior, neurons and networks are right in the middle of this hierarchy.

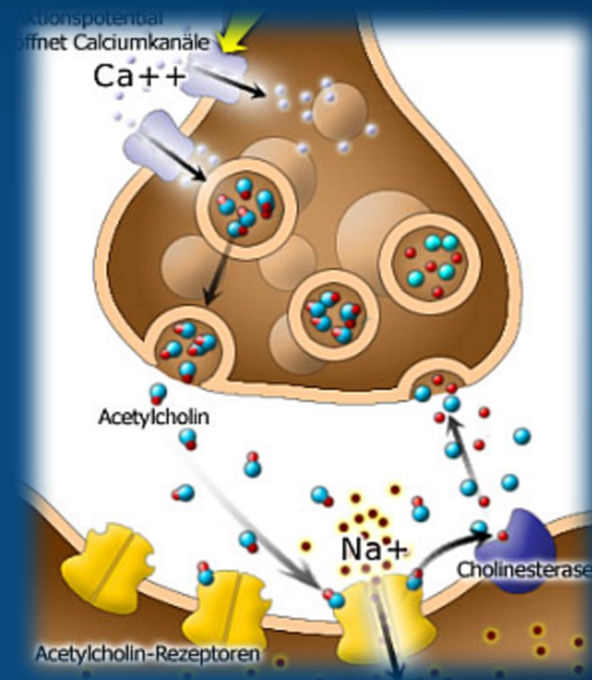
=> Neurodynamics is the key!



From Genes to Neurons

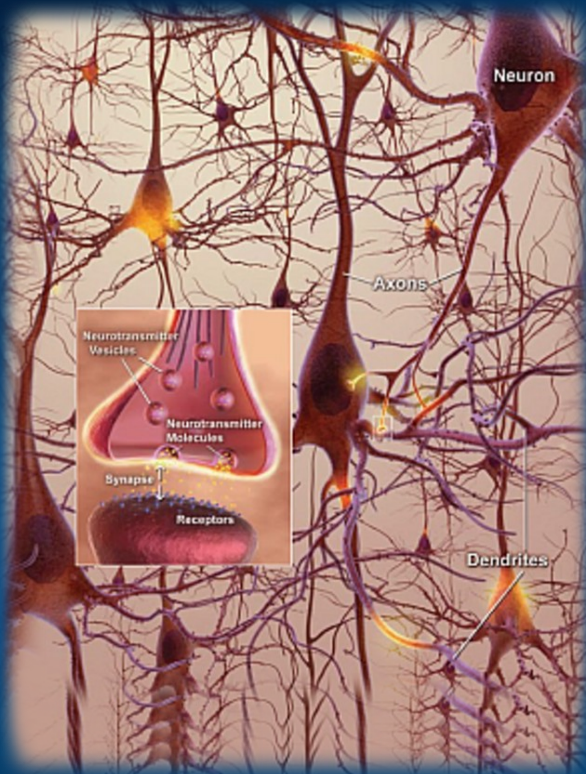


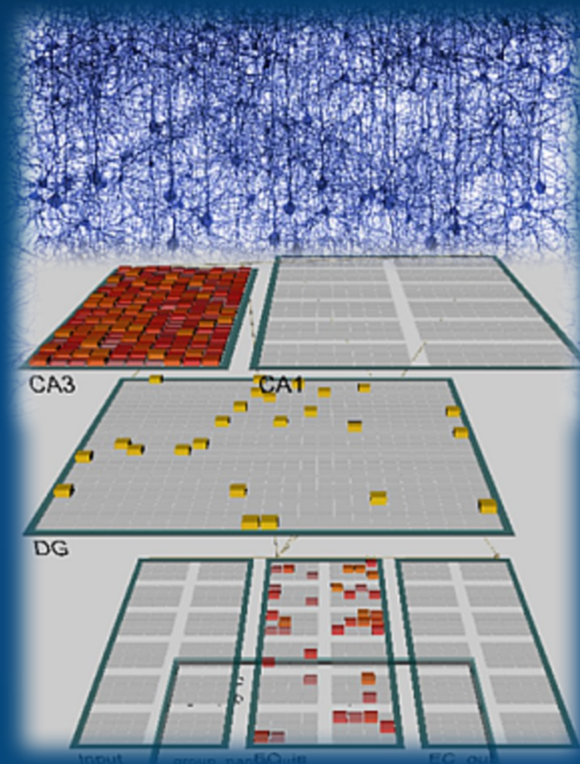


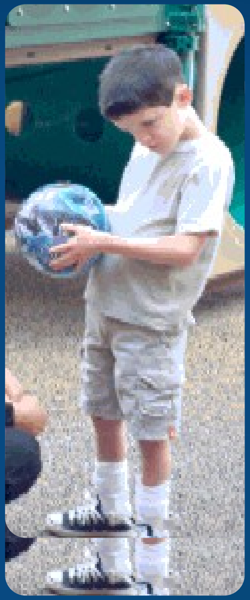


Genes => Proteins => receptors, ion channels, synapses
=> neuron properties, networks, neurodynamics
=> cognitive phenotypes, abnormal behavior, syndromes.

From Neurons to Behavior







Genes => Proteins => receptors, ion channels, synapses
=> neuron properties, networks
=> neurodynamics => cognitive phenotypes, abnormal behavior!

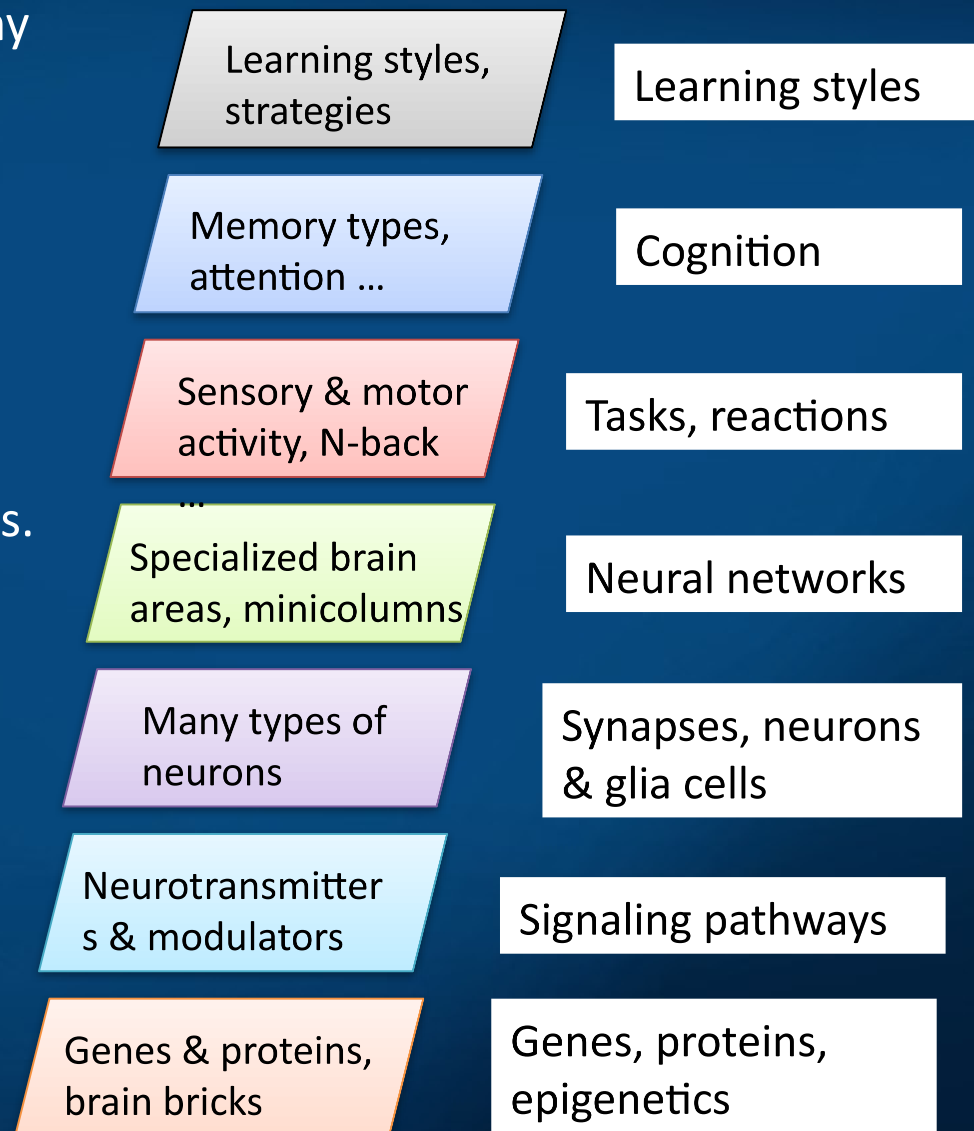
Neurocognitive Phenomics

Phenotypes may be described at many levels. Ex. from top down:
learning styles - education, psychiatry & psychology,
neurophysiology, connectomes, microcircuits, neural networks,
neurobiology - organs, tissues, cells,
biophysics/chemistry & bioinformatics.

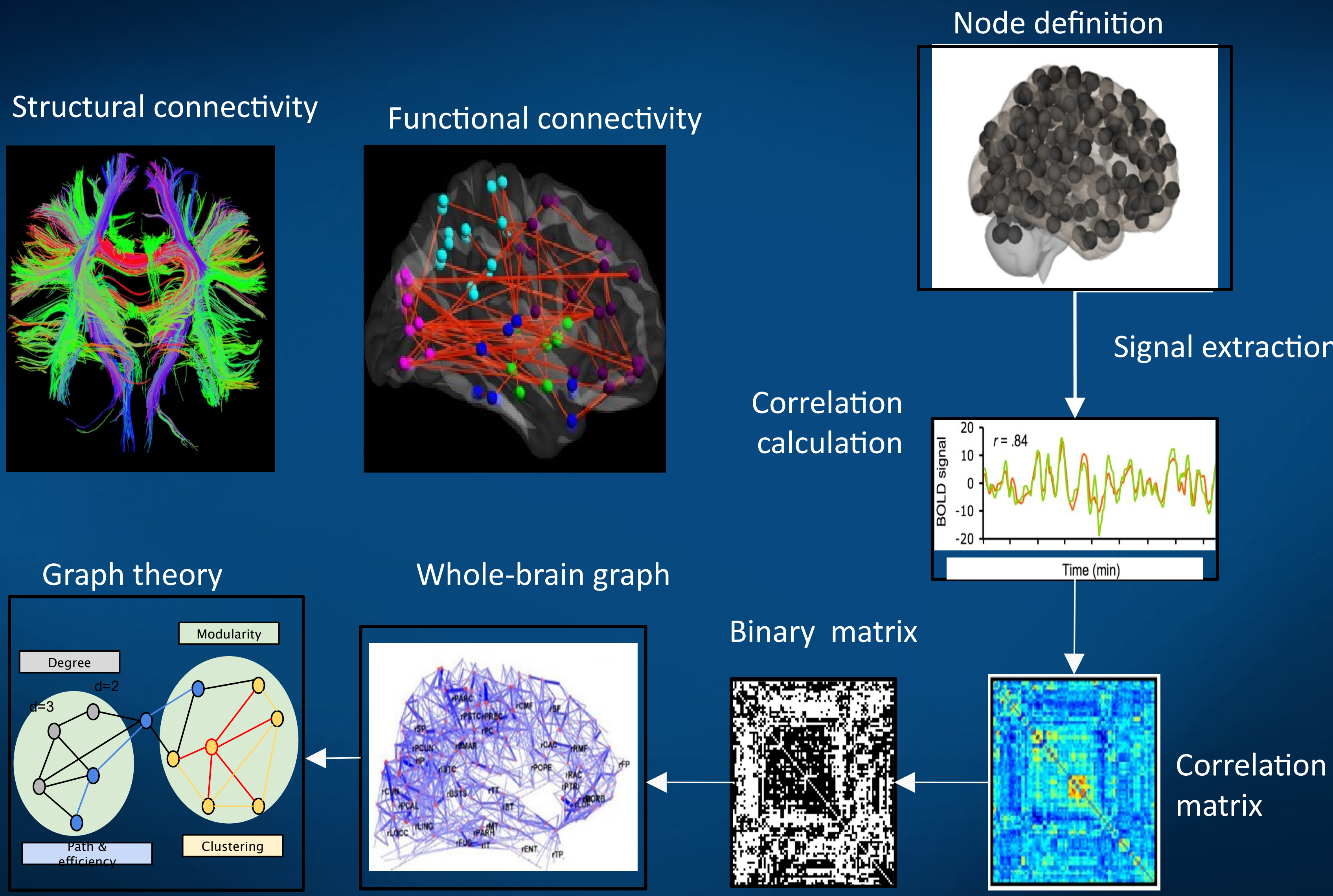
Neurocognitive phenomics is even greater challenge than neuropsychiatric phenomics.

Effects are more subtle but this is the only way to understand fully human/animal behavior.

Data driven science!

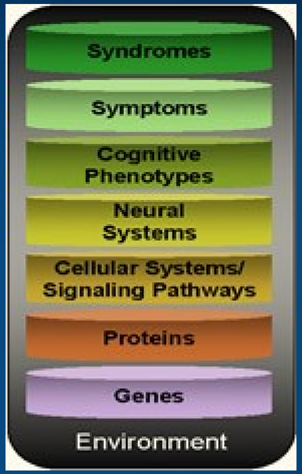


Human connectome and MRI/fMRI



Bullmore & Sporns (2009)

Neurophenomics Research Strategy



The Consortium for Neuropsychiatric Phenomics (2008): bridge all levels, one at a time, from environment to syndromes.

Our strategy: identify biophysical parameters of neurons required for normal neural network functions and leading to abnormal cognitive phenotypes, symptoms and syndromes.

- Start from simple neurons and networks, increase complexity.
- Create models of cognitive function that may reflect some of the symptoms of the disease, for example problems with attention.
- Test and calibrate the stability of these models in a normal mode.
- Determine model parameter ranges that lead to similar symptoms.
- Relate these parameters to the biophysical properties of neurons.

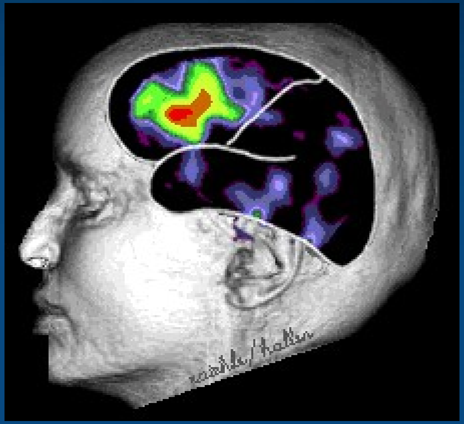
Result: mental events at the network level are described in the language of neurodynamics and related to low-level neural properties.
Example: relation of ASD/ADHD symptoms to neural accommodation.

Geometric model of mind

Objective ⇔ Subjective.

Brain ⇔ Mind.

Neurodynamics describes state of the brain activation measured using EEG, MEG, NIRS-OT, PET, fMRI or other techniques.

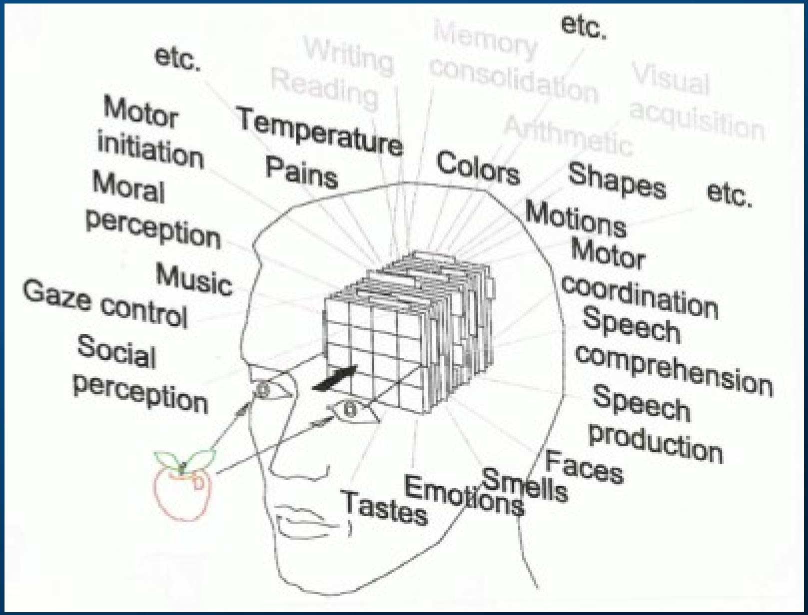


Mind states=f(Brain states)

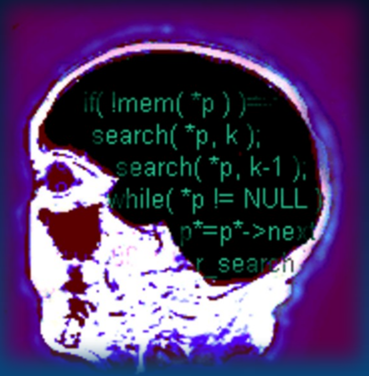
How to represent mind state?

In the space based on dimensions that have subjective interpretation: intentions, emotions, qualia.

Mind state and brain state trajectory should then be linked together by some transformations, like in the Brain-Computer Interfaces.



Neurocognitive informatics



Use inspirations from the brain, derive practical algorithms!

My own attempts - see my webpage, Google: W. Duch

1. Mind as a shadow of neurodynamics: geometrical model of mind processes, psychological spaces providing inner perspective as an approximation to neurodynamics.
2. Intuition: learning from partial observations, solving problems without explicit reasoning (and combinatorial complexity) in an intuitive way.
3. Neurocognitive linguistics: how to find neural pathways in the brain.
4. Creativity in limited domains + word games, good fields for testing.

Duch W, Intuition, Insight, Imagination and Creativity,
IEEE Computational Intelligence Magazine 2(3), 2007, pp. 40-52

Genes=>Proteins

~$5\text{x}10^{13}$=50T cells, 2m DNA/cell

~10^{14}m=100 T km = 666 au!

~10^{15}=1P synapses;

>1M new synapses/sec

~100G neuronów (10^{11})

>550.000 structures in Swiss-proteome database

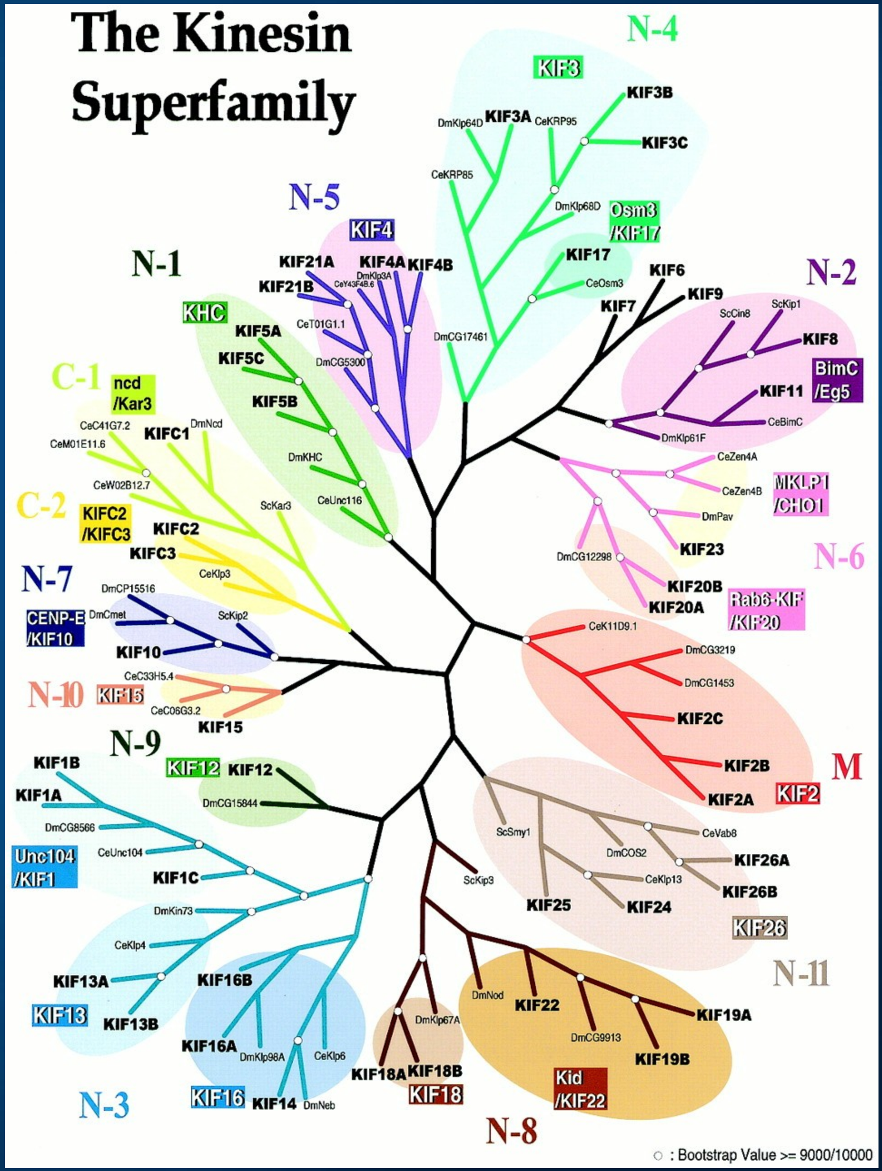
~60.000 protein families

~20.000 genes

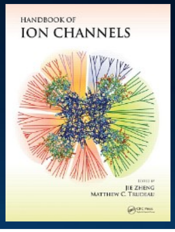
>100.000 proteins/cells

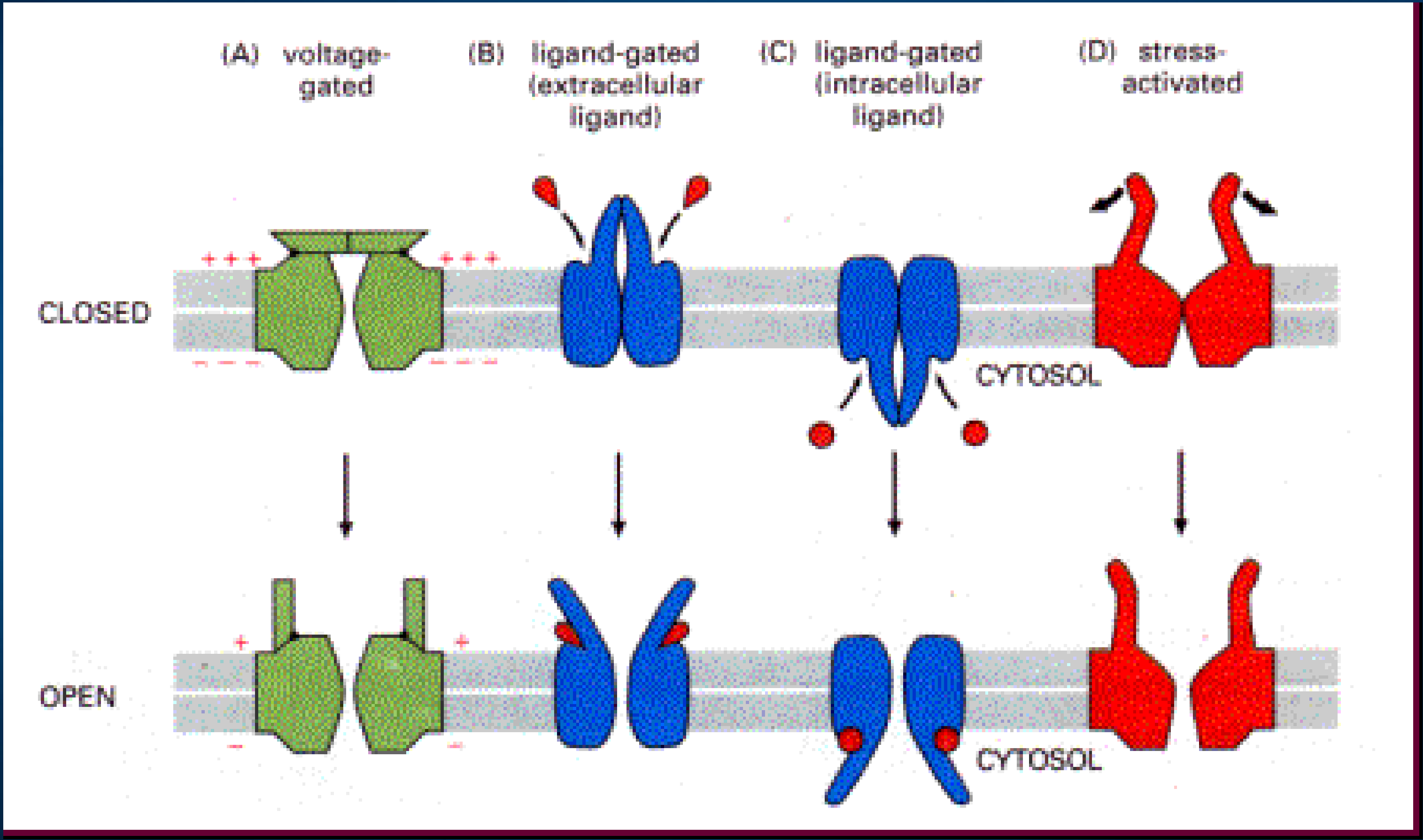
Organism is a process!

lifetime 4 days to >100 years.

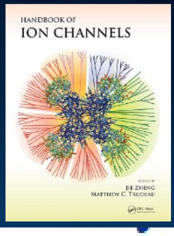


Ion channel types

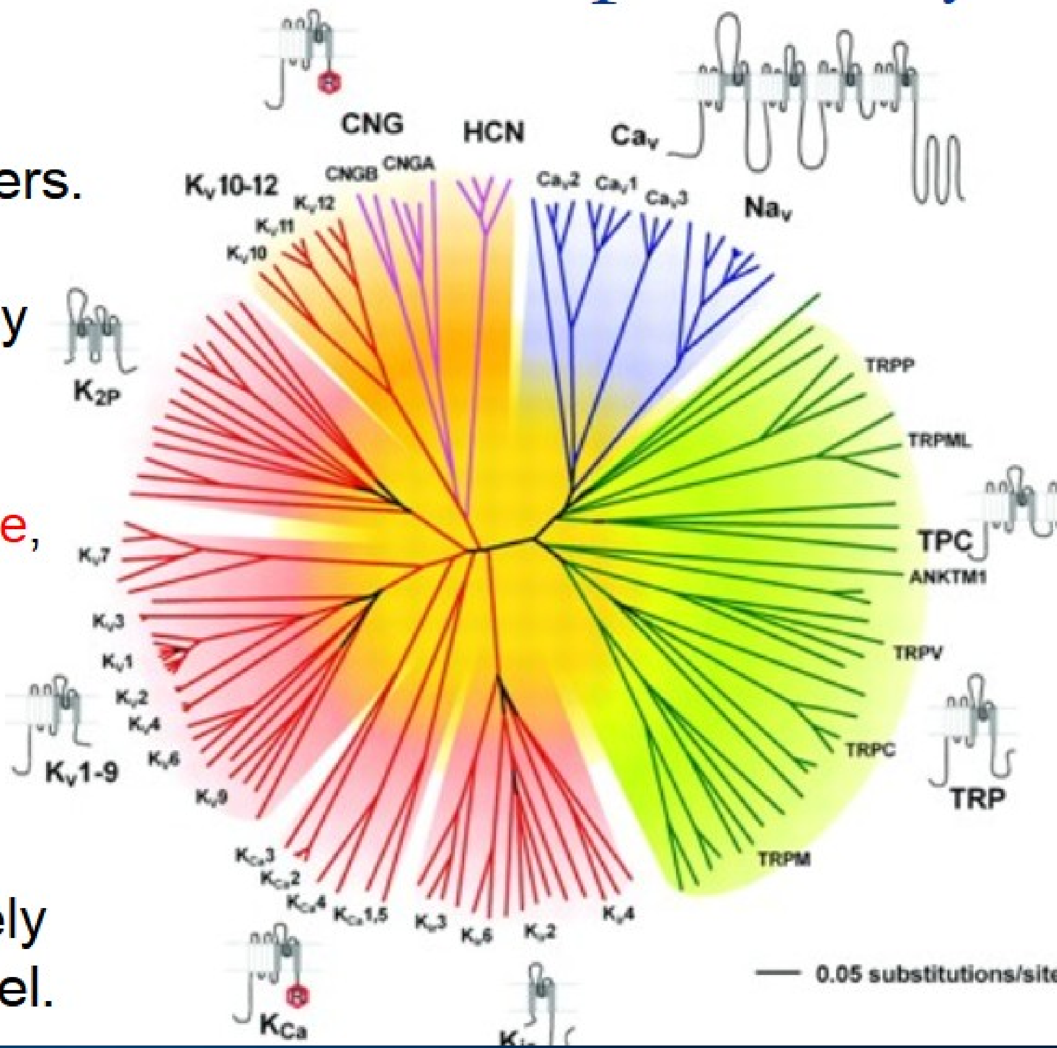




Voltage-gated ion channels



- More than 140 members.
- Conductance varies by 100 fold.
- Variable gating: voltage, 2nd messengers, stimuli (pH, heat, tension, etc.)
- $K_L \rightarrow Ca_v \rightarrow Na_v$
- Bacterial ancestor likely similar to KcsA channel.



Computational Models

Models at various level of detail.

- Minimal model includes neurons with 3 types of ion channels.

Models of attention:

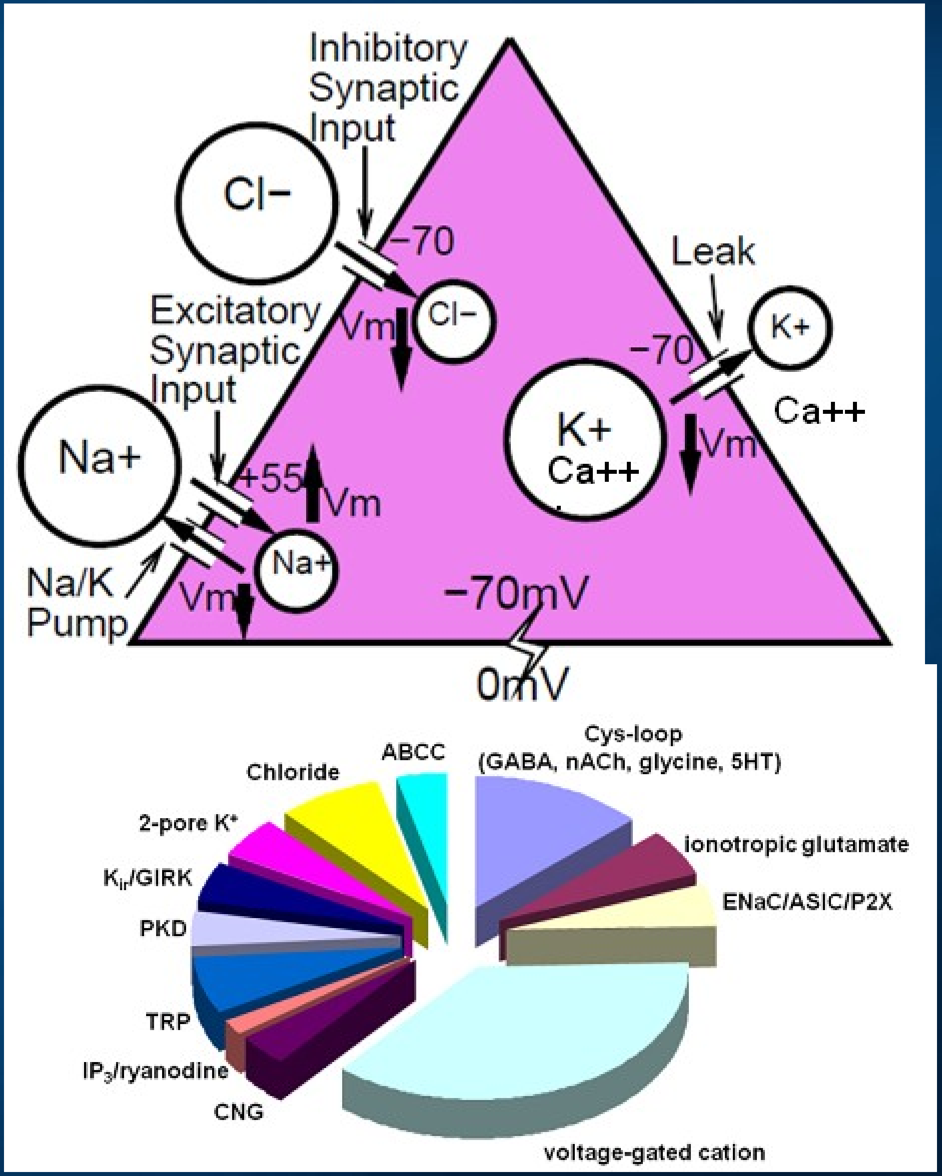
- Posner spatial attention;
- attention shift between visual objects.

Models of word associations:

- sequence of spontaneous thoughts.

Models of motor control.

Critical: control of the increase in intracellular calcium, which builds up slowly as a function of activation. Initial focus on the leak channels, 2-pore K^+, looking for genes/proteins.



Model of reading & dyslexia

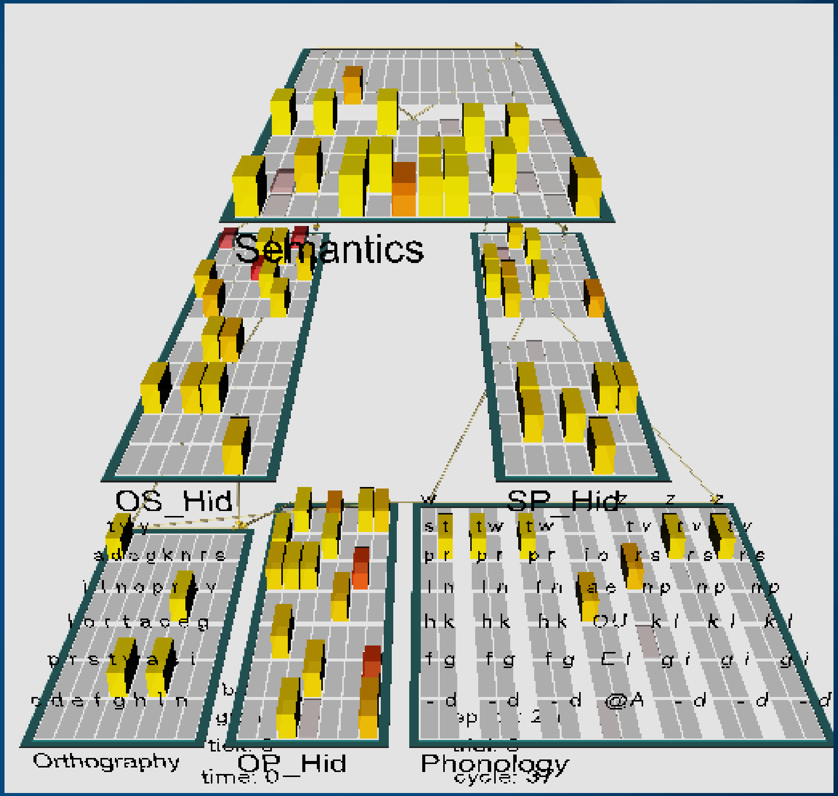
Emergent neural simulator:

Aisa, B., Mingus, B., and O'Reilly, R. The emergent neural modeling system. Neural Networks, 21, 1045-1212, 2008.

3-layer model of reading:

orthography, phonology, semantics, or distribution of activity over **140 microfeatures** defining concepts.

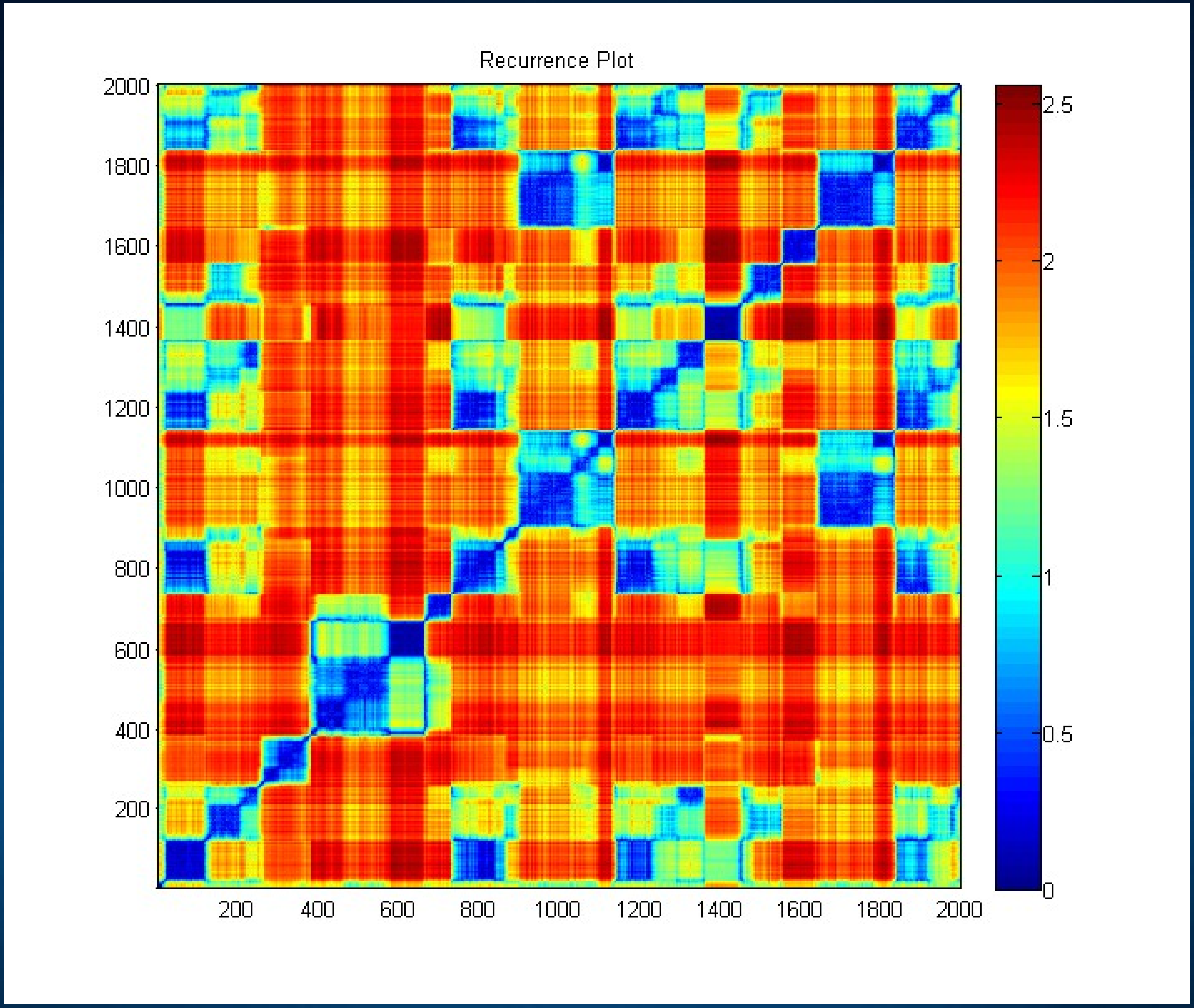
Hidden layers in between.



Learning: mapping one of the 3 layers to the other two.

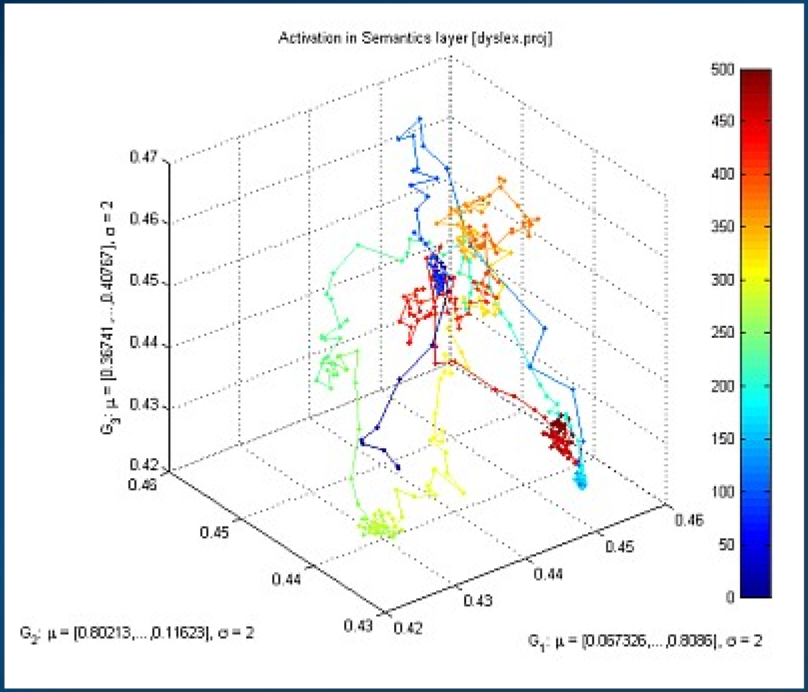
Fluctuations around final configuration = attractors representing concepts.

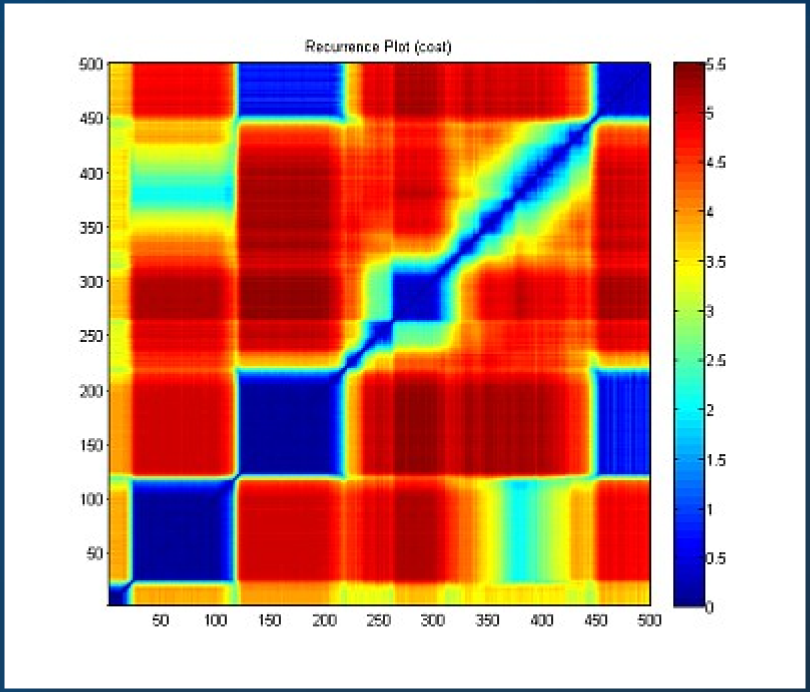
How to see properties of their basins, their relations?



„Gain”: trajectory of semantic activations quickly changes to a new synchronized activity, periodically returns to the first basin of attraction.

Fast transitions

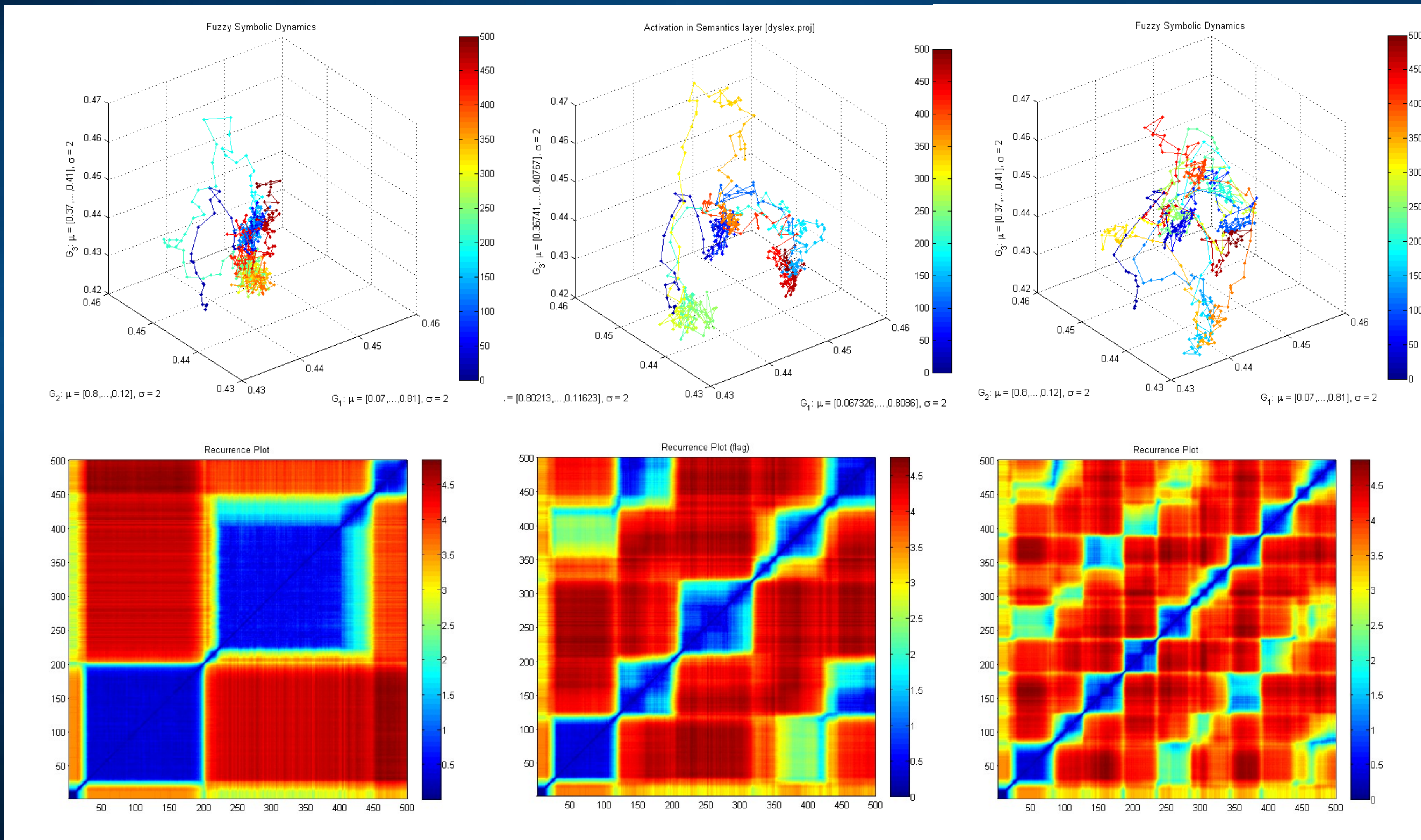




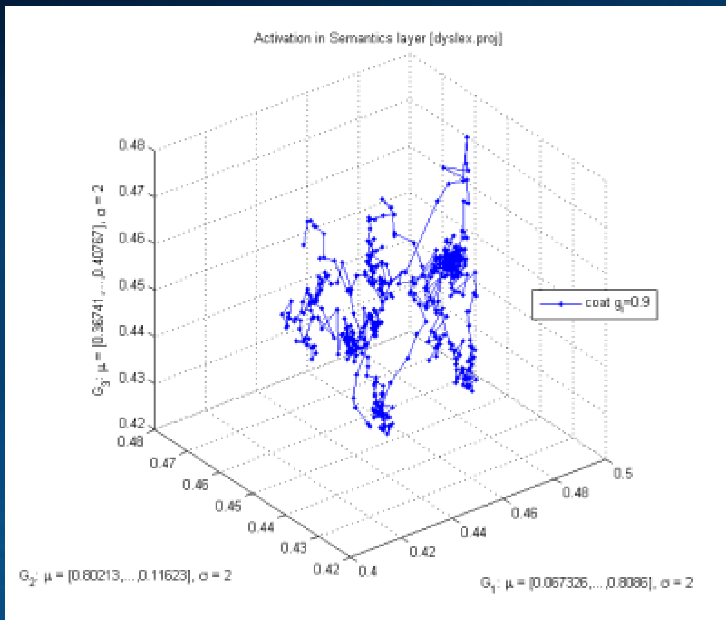
Attention is focused only for a brief time and than moved to the next attractor basin, some basins are visited for such a short time that no action may follow, no chance for other neuronal groups to synchronize. This corresponds to the feeling of confusion, not being conscious of fleeting thoughts.

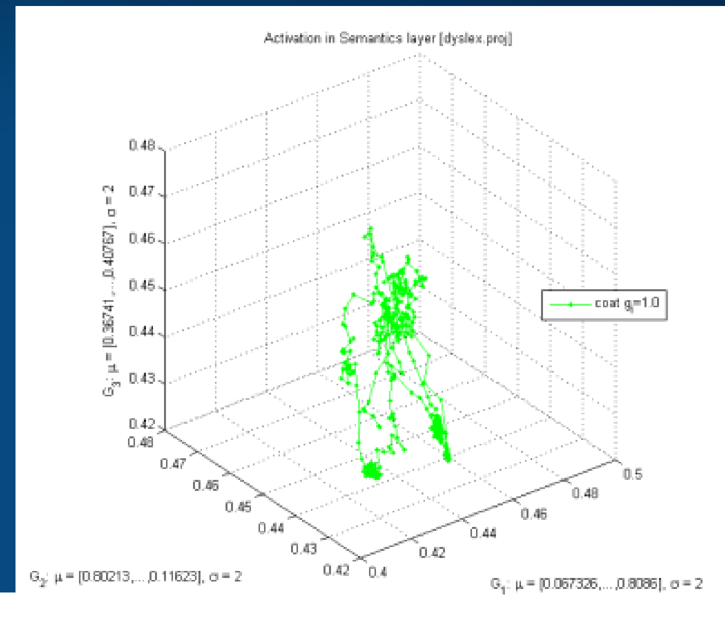
Autism-Normal-ADHD

b_inc_dt = 0.005 | *b_inc_dt* = 0.01 | *b_inc_dt* = 0.02

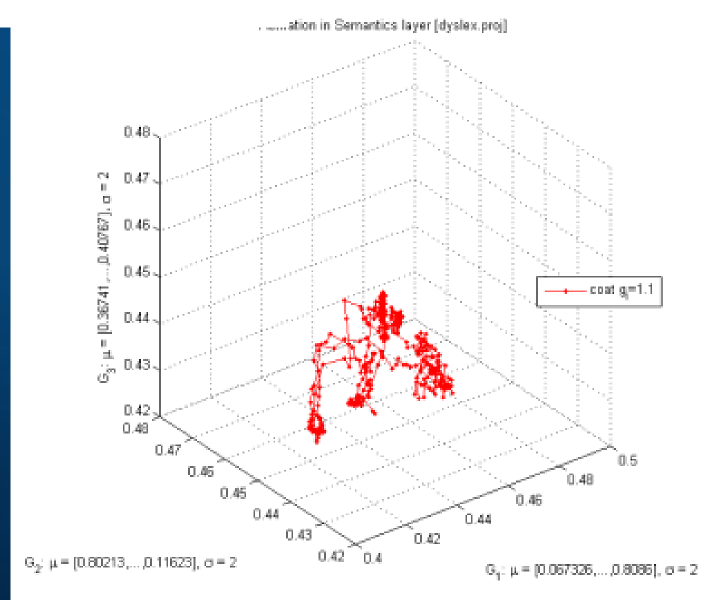


Inhibition



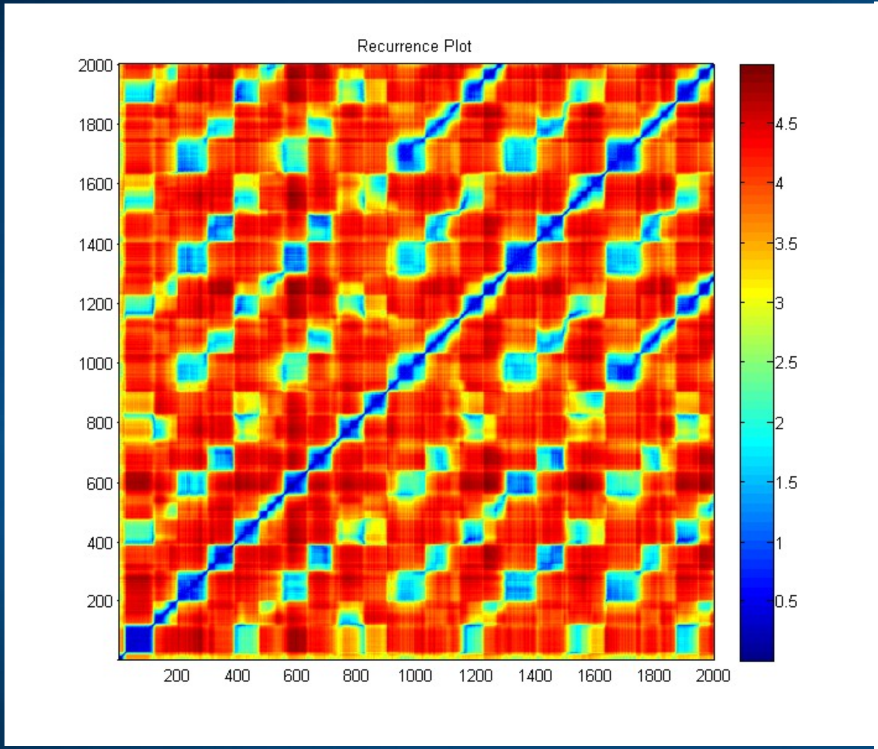


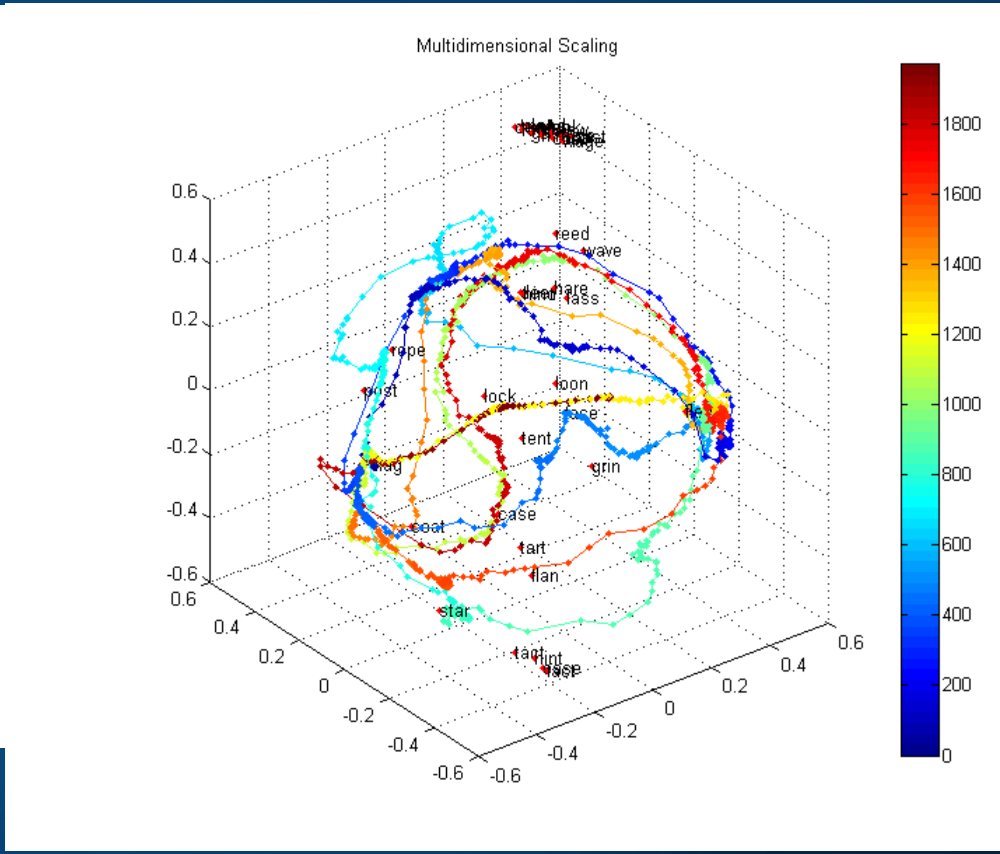
Increasing g_i from 0.9 to 1.1 reduces the attractor basin sizes and simplifies trajectories.



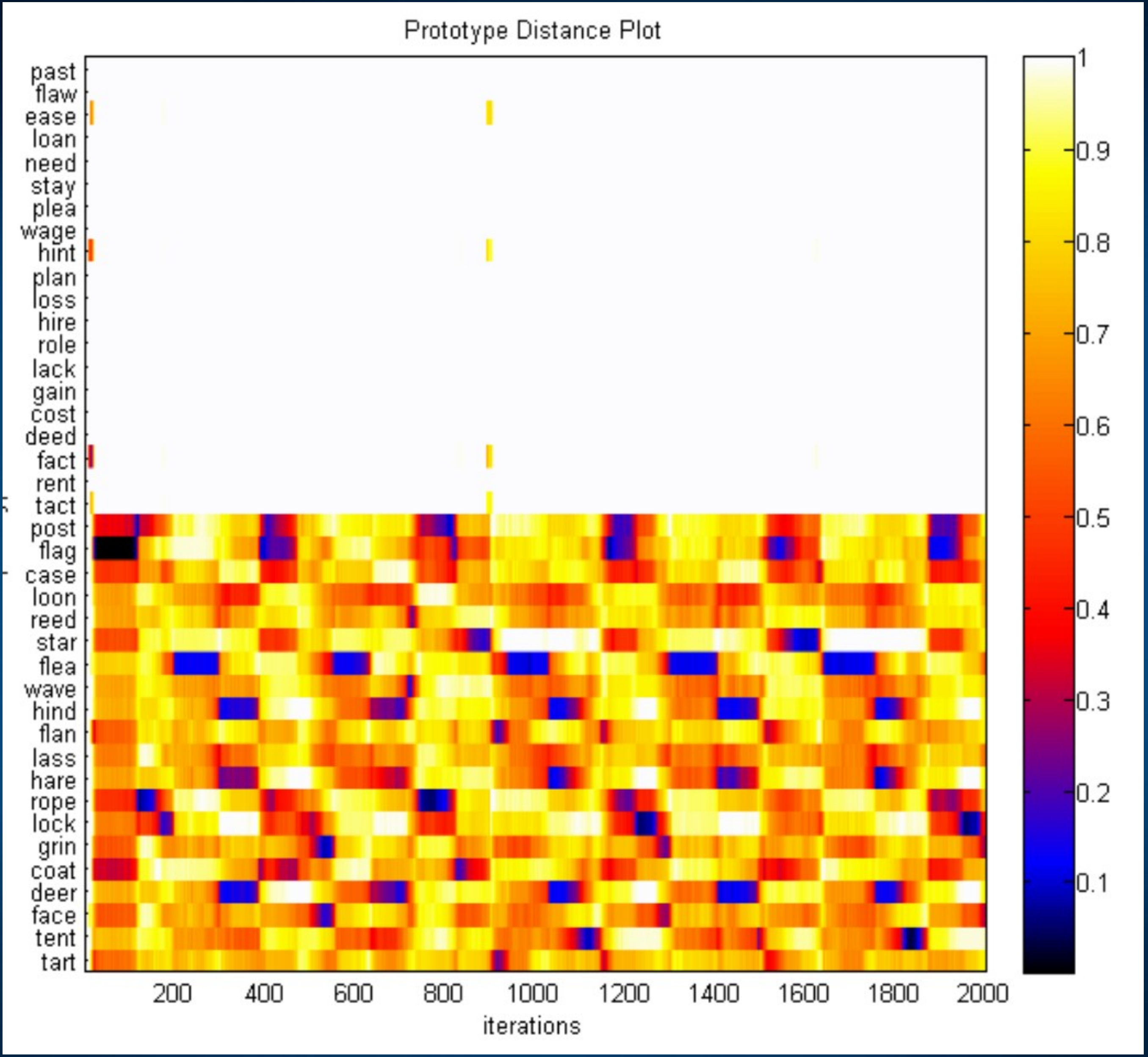
Strong inhibition, empty head …

Long trajectories





Recurrence plots and MDS visualization in 40-words microdomain, starting with the word “flag”.

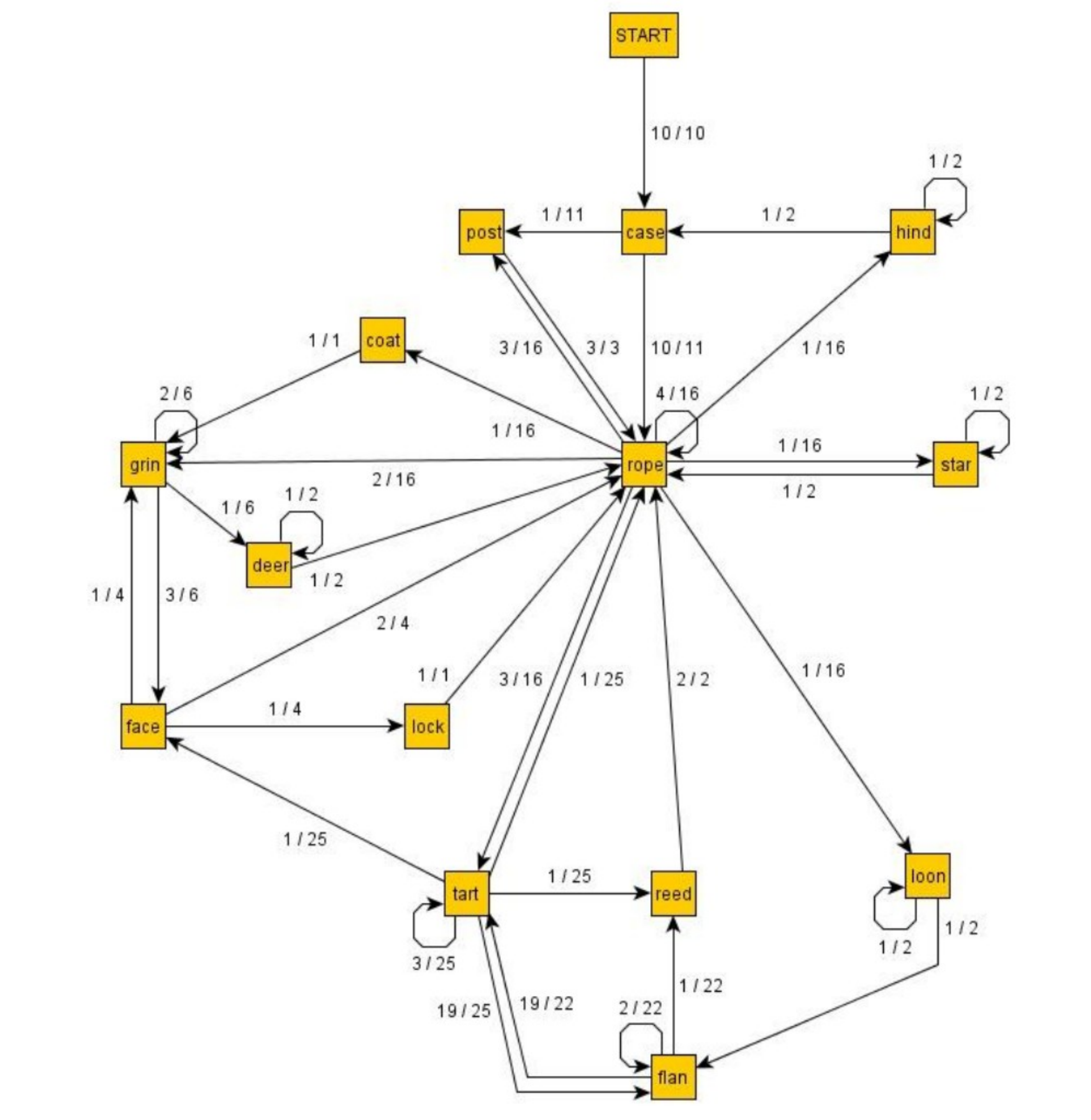


PDP for transitions starting from „flag"

Transitions between attractors after 10 runs.

Why these particular transitions?

Connected attractors share some microfeatures, some are deactivated, but visualization using RP or FSD does not show such details.
In the phase space dimensions are rescaled during dynamics.



MDS word mapping

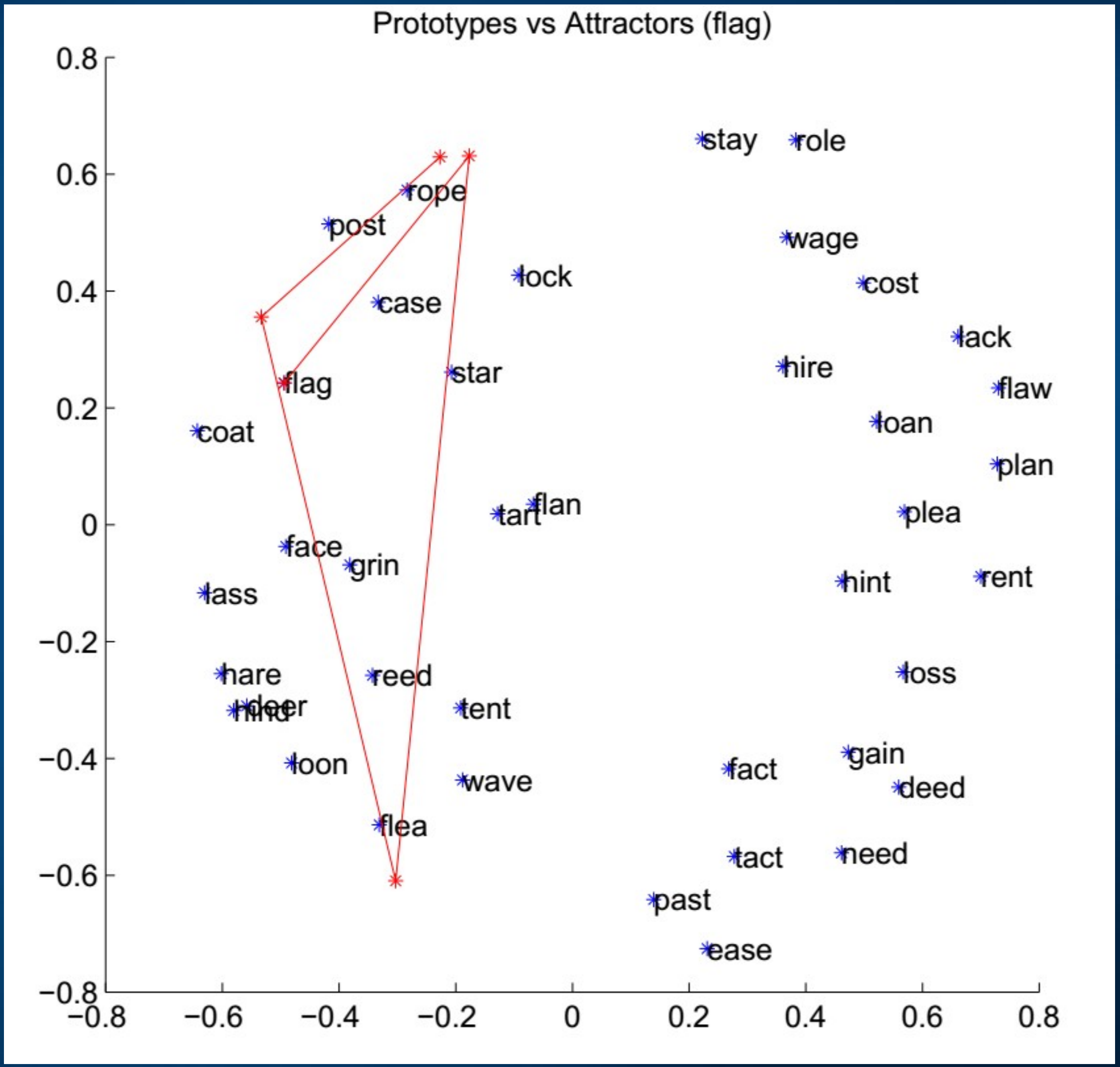
MDS representation of all 40 words, showing similarities of their 140 dimensional vectors.

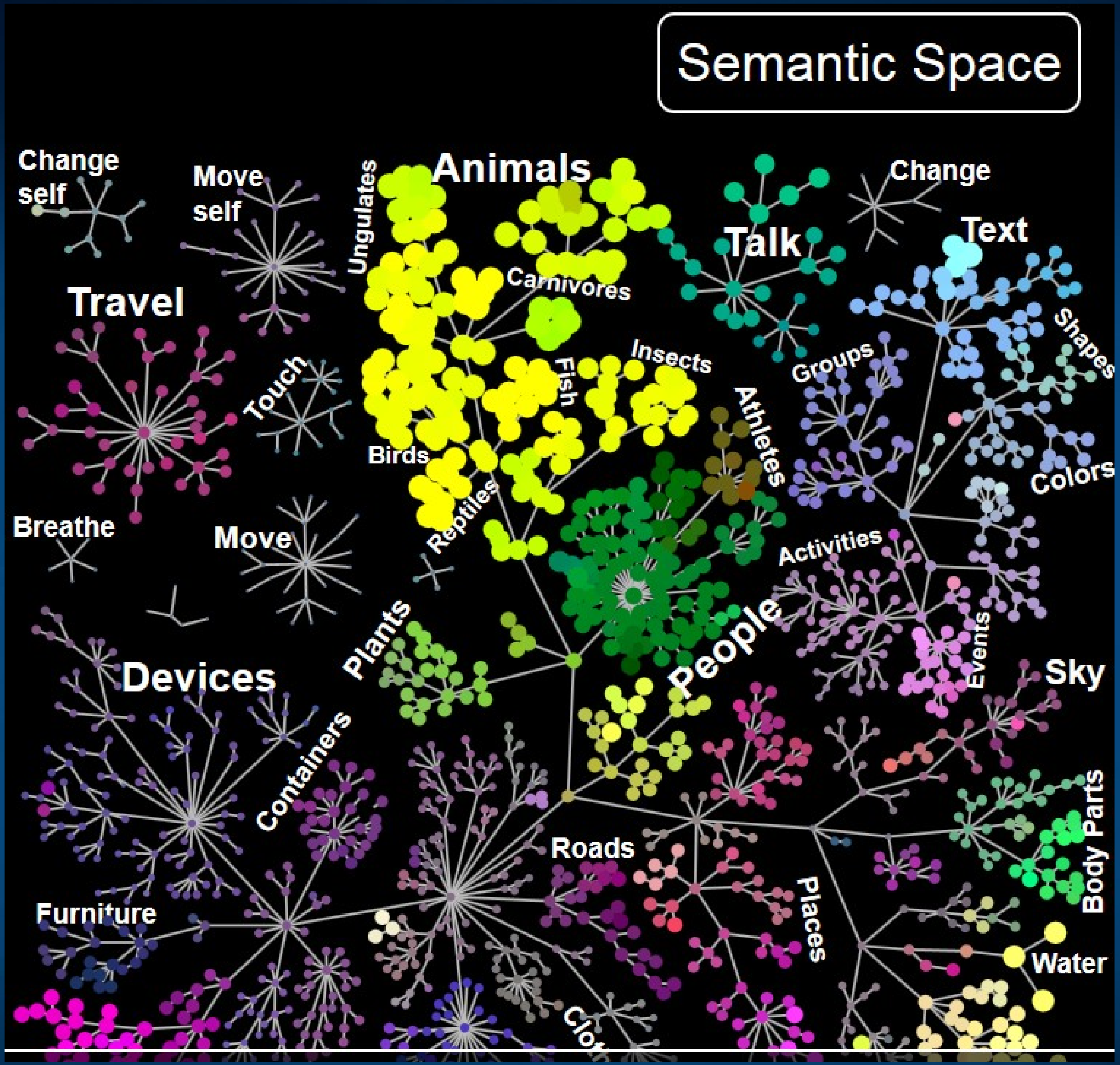
Attractors are in some cases far from words.

Transition

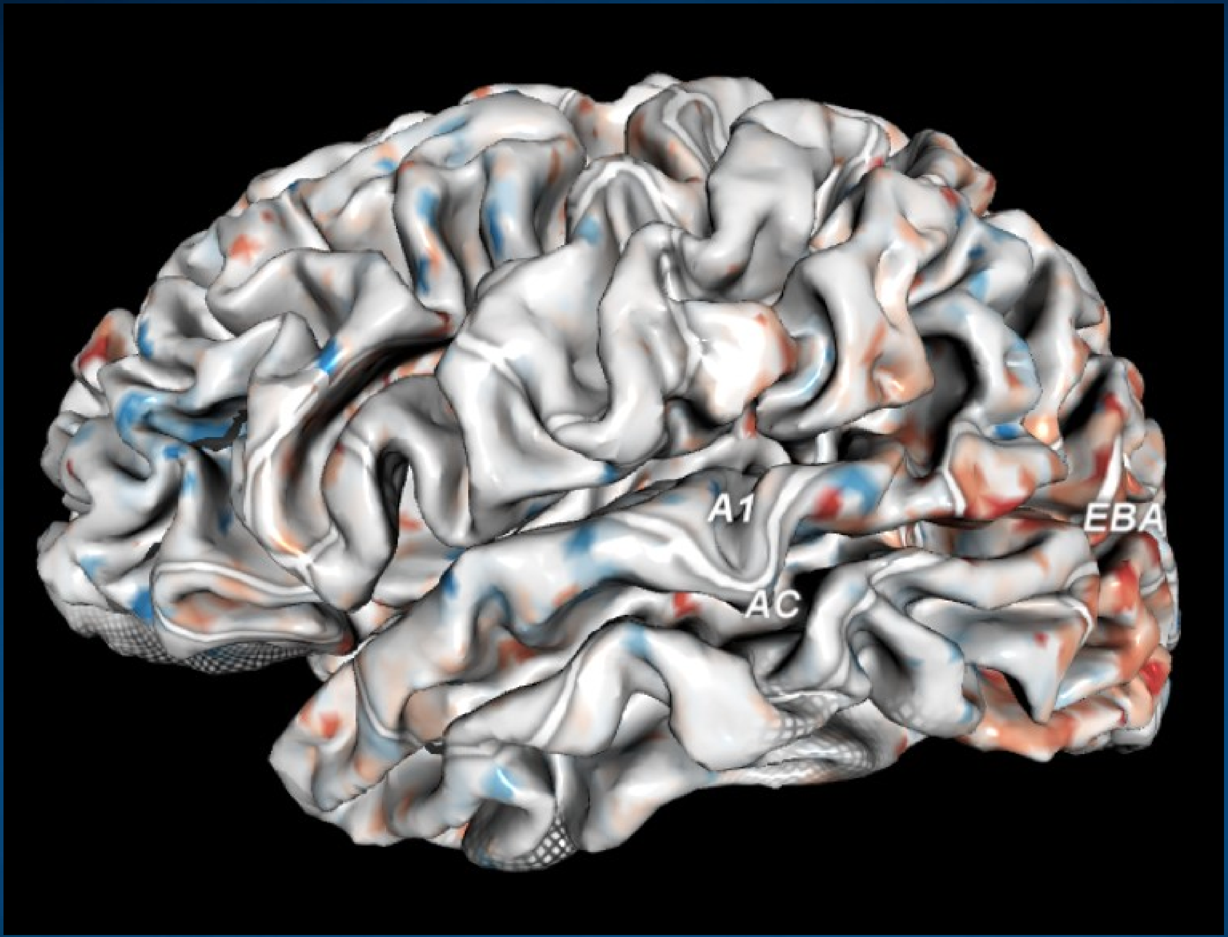
Flag => rope => flea ...

Can we make semantic map of concepts in real brains? See trajectories of thought?

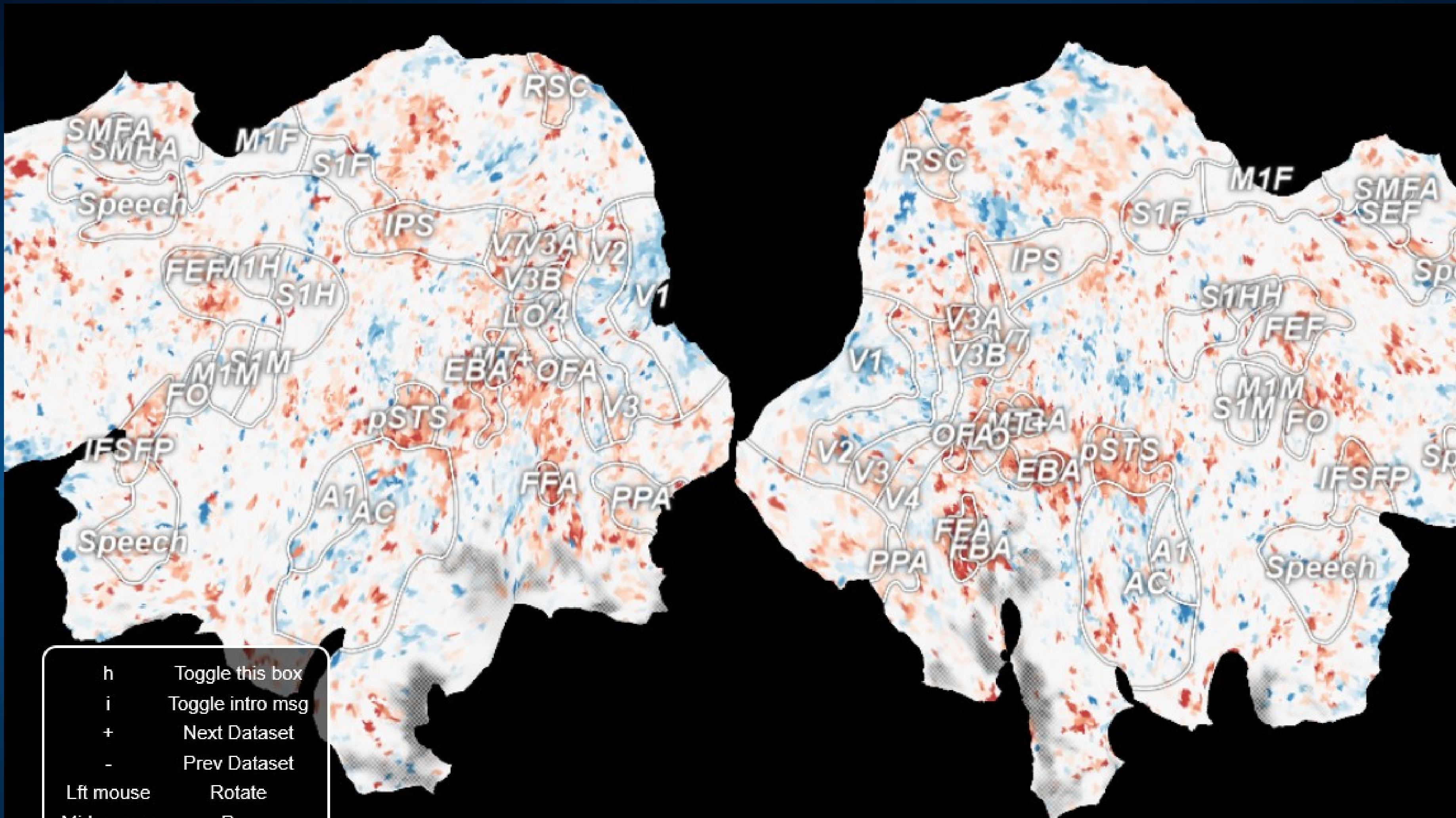




Activation of concepts in our minds leads to specific brain structure activity; each structure is involved in interpretation of many concepts.



Activation of specific concept (mental state) leads to activation of specific brain structures. Each structure contributes to sematic interpretation of many concepts through global brain activity.



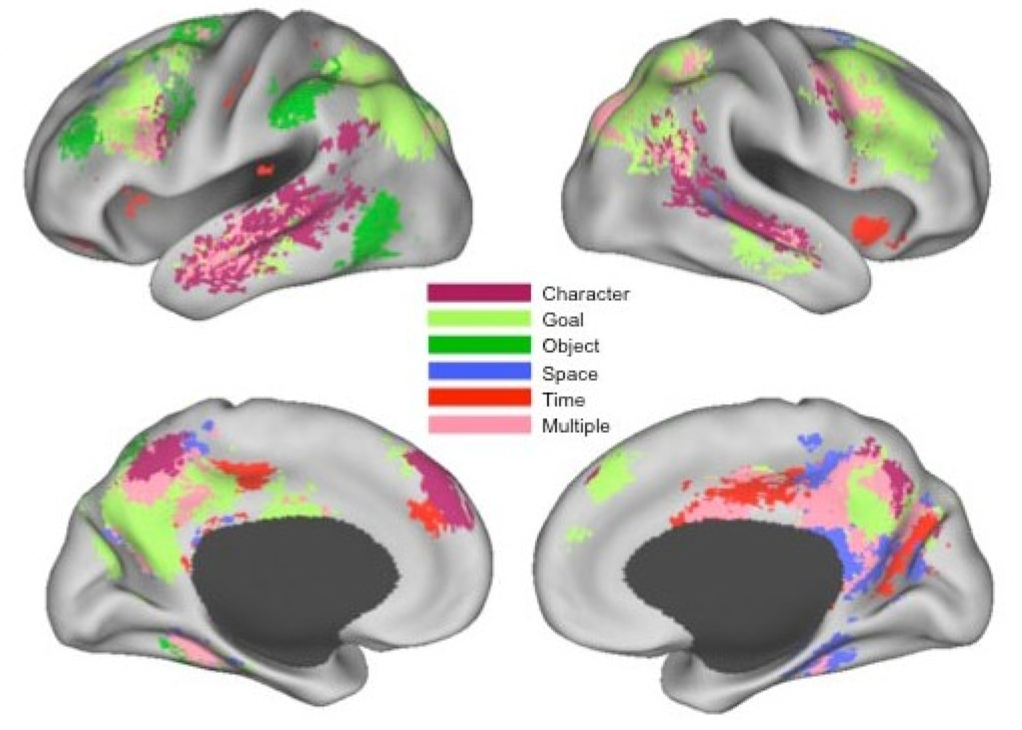
This activation is sparse and may be better observed by looking at the flattened cortex: http://gallantlab.org/brainviewer/huthetal2012/

Nicole Speer et al.
Reading Stories Activates Neural Representations of Visual and Motor Experiences.
Psychological Science 2009; 20(8): 989–999.
Meaning: always slightly different, depending on the context, but still may be clusterized into relatively samll number of distinct meanings.

A

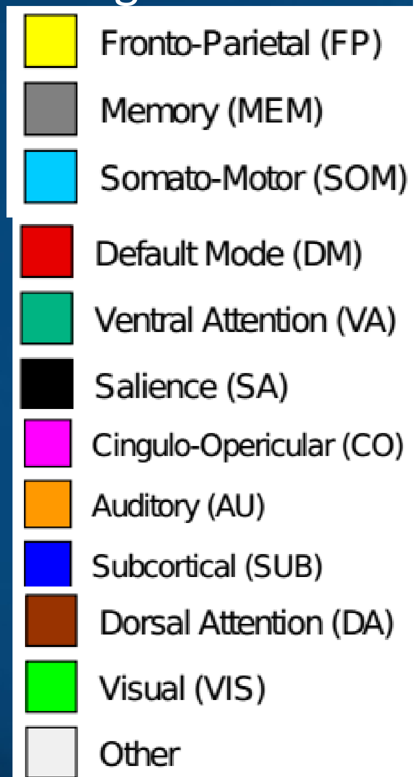
Clause	Cause	Character	Goal	Object	Space	Time
...[Mrs. Birch] went through the front door into the kitchen.	•				•	
Mr. Birch came in	•	•			•	
and, after a friendly greeting,	•					•
chatted with her for a minute or so.	•					•
Mrs. Birch needed to awaken Raymond.		•				
Mrs. Birch stepped into Raymond's bedroom,			•		•	
pulled a light cord hanging from the center of the room,				•		
and turned to the bed.						
Mrs. Birch said with pleasant casualness,						
"Raymond, wake up."						
With a little more urgency in her voice she spoke again:						
Son, are you going to school today?						
Raymond didn't respond immediately.		•				•
He screwed up his face			•			
And whimpered a little.						

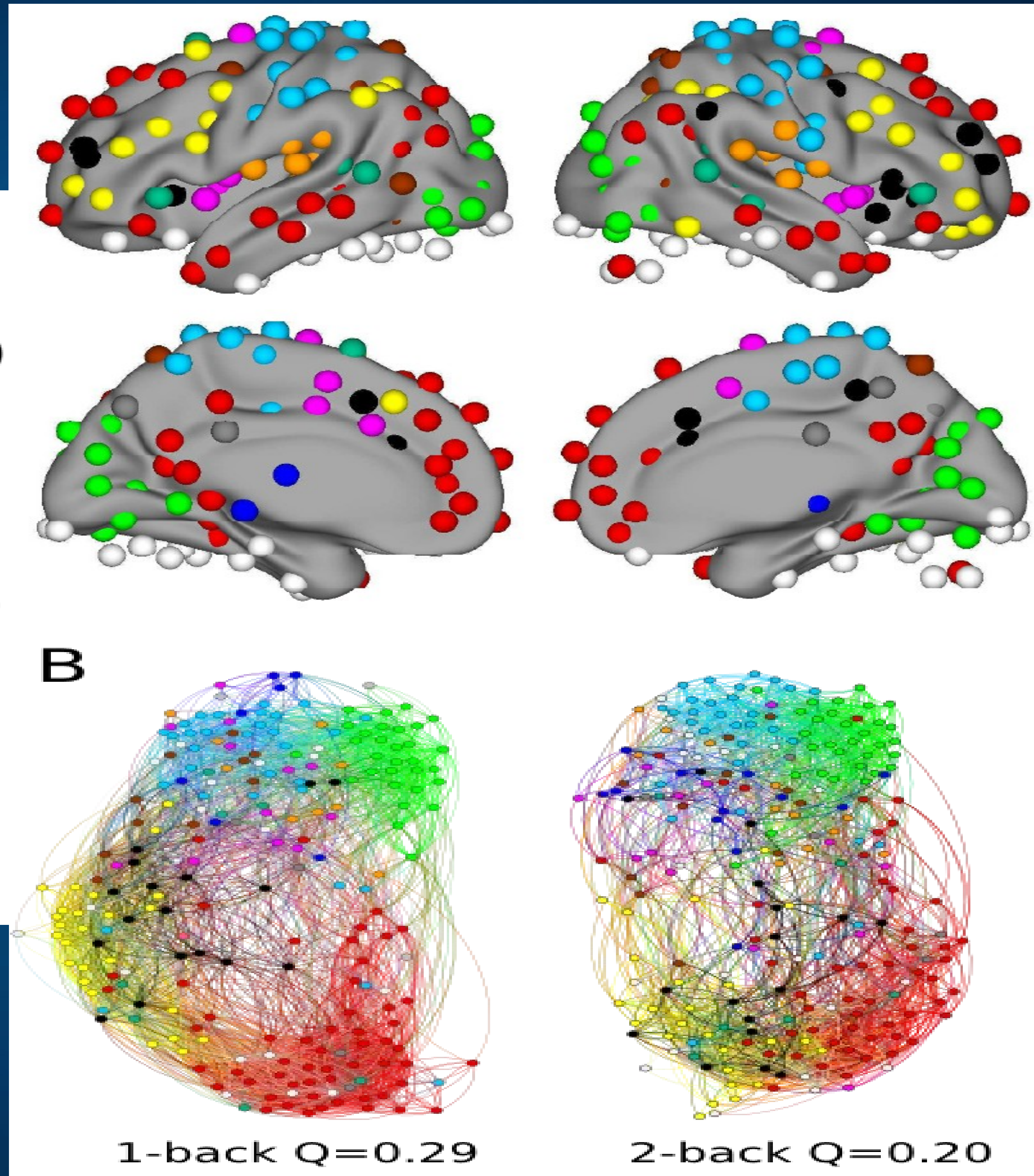
B



Brain modules and cognitive processes

Simple and more difficult tasks, requiring the whole-brain network reorganization.





Left: 1-back

Right: 2-back

Average over 35 participants.

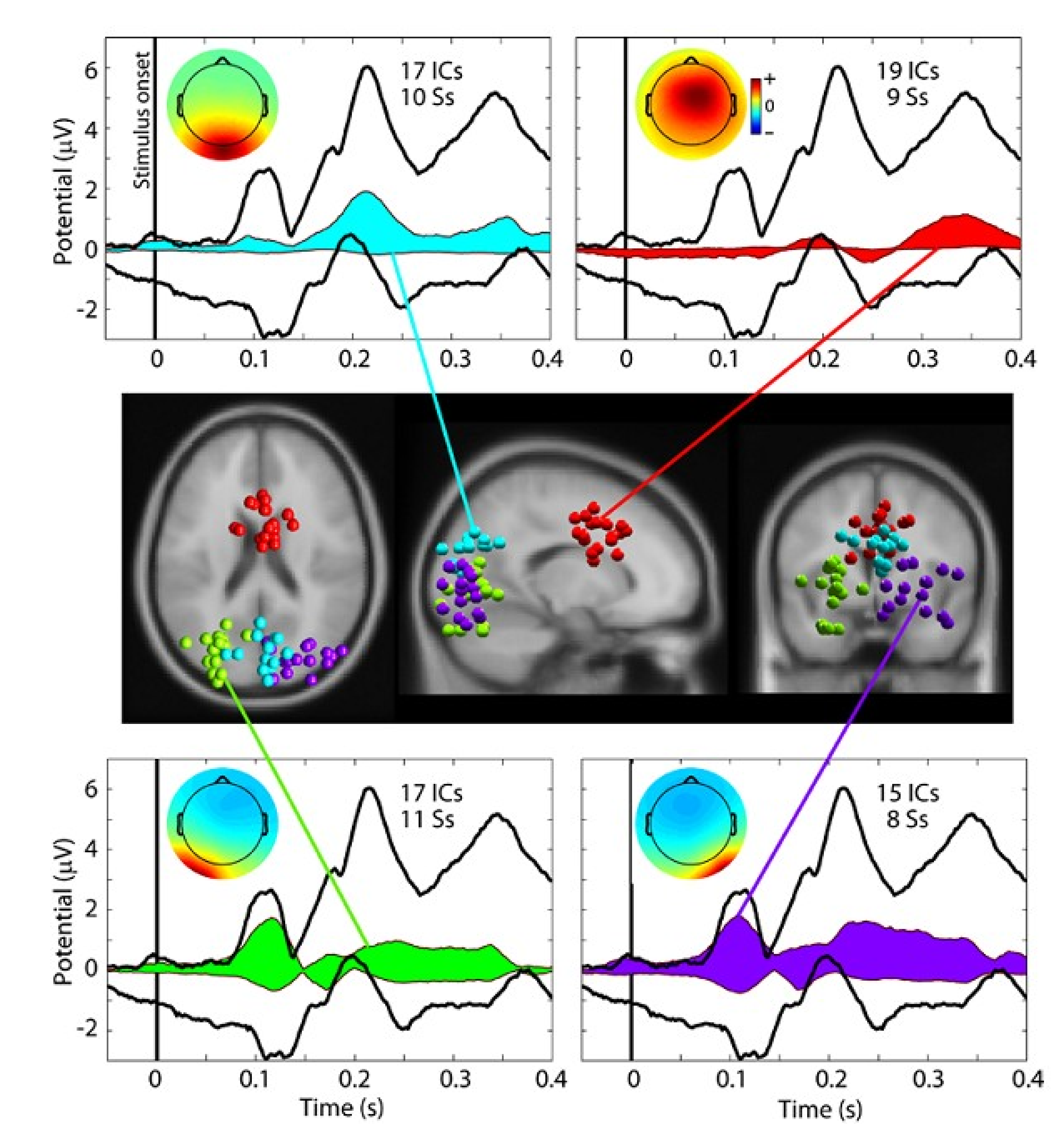
Left and midline sections.

K. Finc et al (HBM, in rev, with World Hearing Center, MPI for Human Development).

Source localization maps brain activity to attractor dynamics.

Problem: these sources pop up and vanish in different places.

Fig. from:
Makeig, Onton, ERP Features and EEG Dynamics: An ICA Perspective, 2009

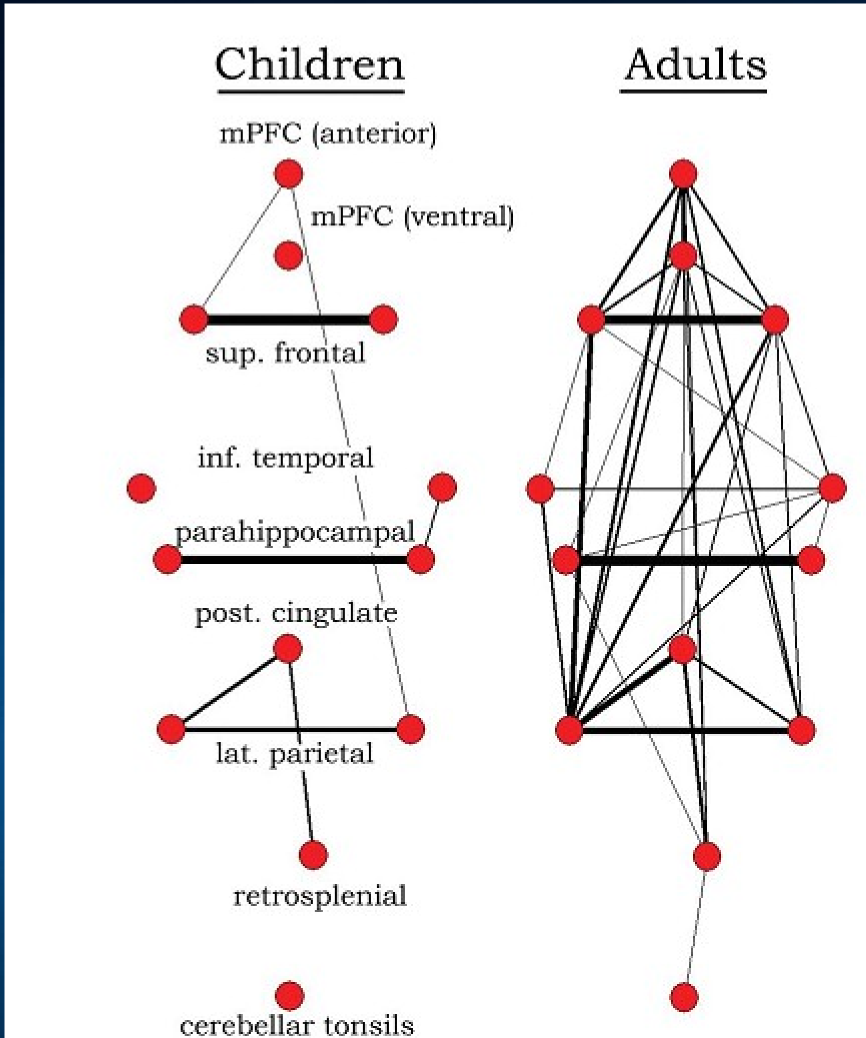


Origin of the learning styles

Connectomes develops before birth and in the first years of life.

Achieving harmonious development is very difficult and depends on low-level (genetic, epigenetic, signaling pathways) processes, but may be influenced by experience and learning.

- Excess of low-level (sensory) processes S⇔S.
- Poor C⇔C neural connections and synchronization, frontal⇔parietal necessary for abstract thinking, weak functional connections prefrontal lobe ⇔ other areas.
- Patterns of activation in the brain differ depending on whether the brain is doing social or nonsocial tasks.
- “Default brain network” involves a large-scale brain network (cingulate cortex, mPFC, lateral PC), shows low activity for goal-related actions; strong activity in social and emotional processing, mindwandering, daydreaming.



earning styles

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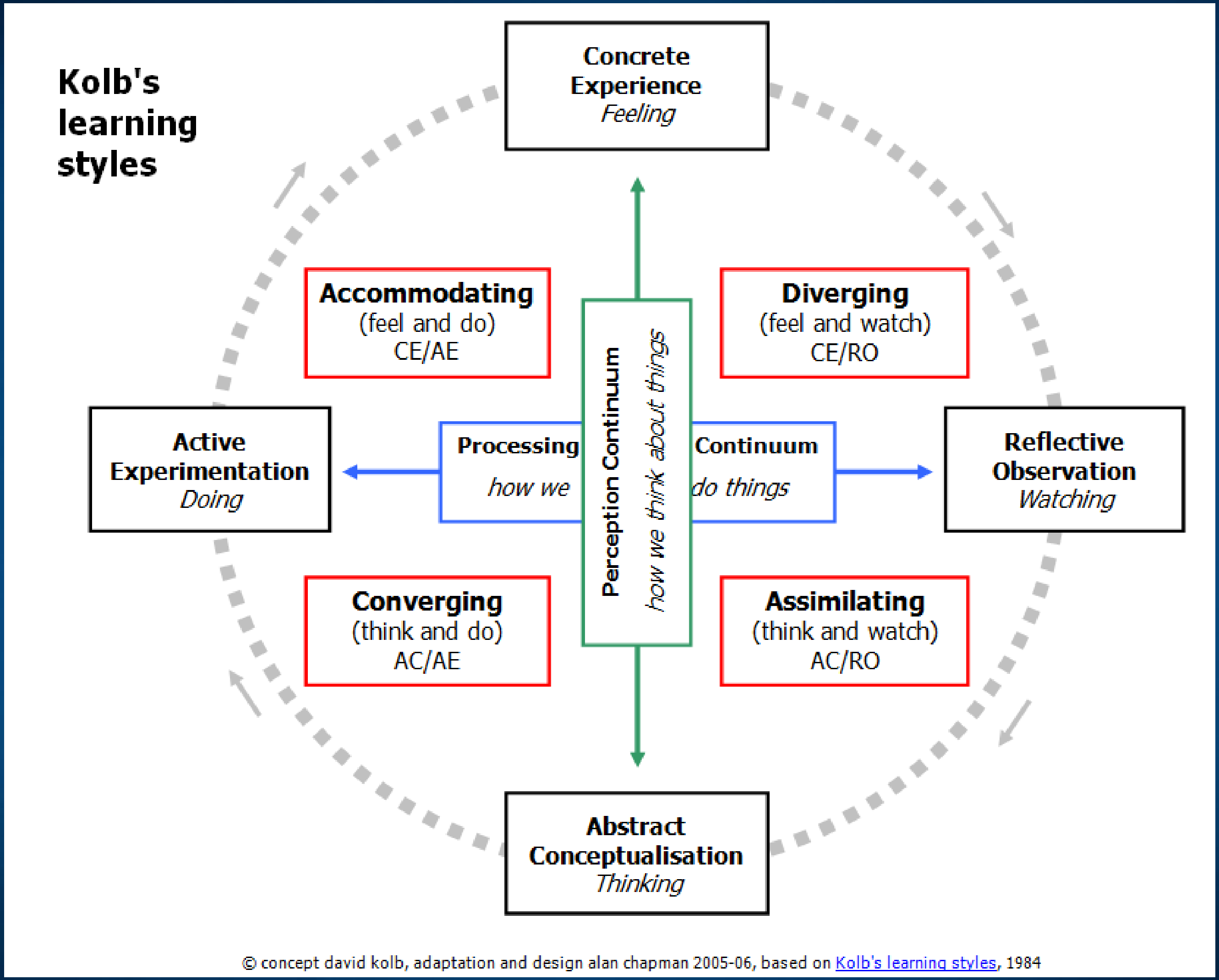
Learning styles



David Kolb, *Experiential learning: Experience as the source of learning and development* (1984), and *Learning Styles Inventory*.

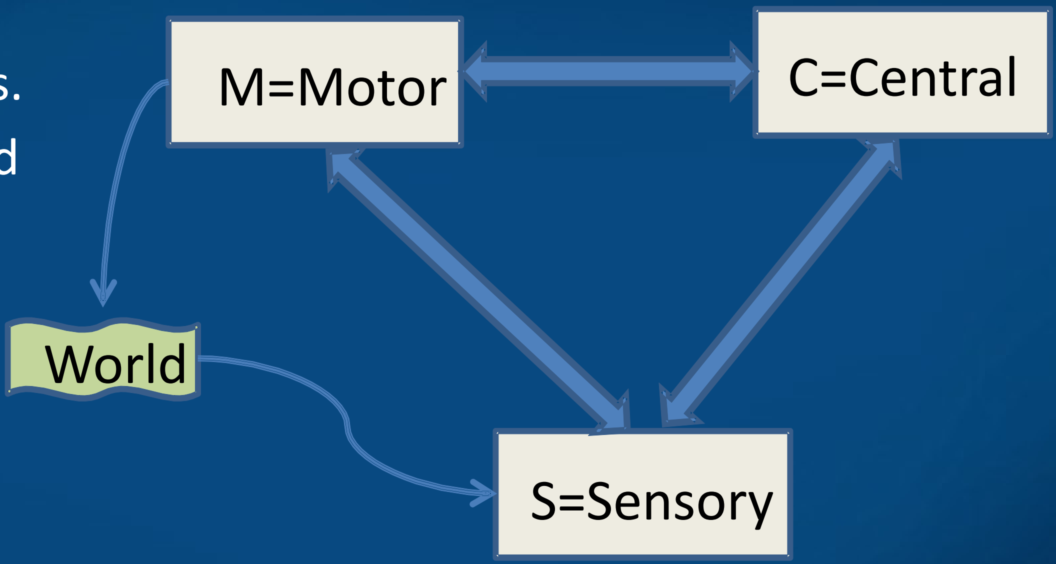
Connectome and learning styles

Simple connectome models may help to connect and improve learning classification of the styles.

S, Sensory level, occipital, STS, and somatosensory cortex;

C, central associative level, abstract concepts that have no sensory components,

mostly parietal, temporal and prefrontal lobes.



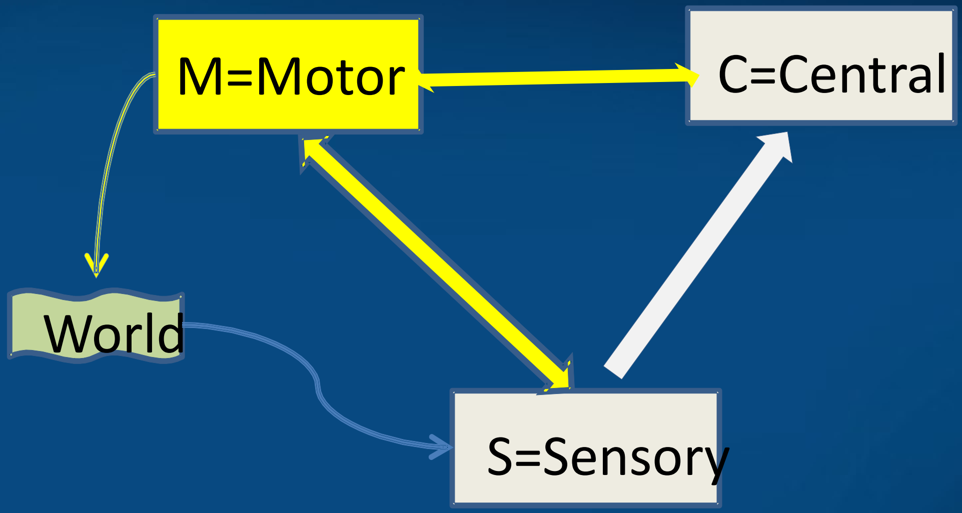
M, motor cortex, motor imagery & physical action.
Frontal cortex, basal ganglia.

Even without emotion and reward system predominance of activity within or between these areas explains many learning phenomena.

Learning styles D1

Kolb passive-active dimension, observation – experimentation: motor-central processes M⇔C, sensory-motor processes M⇔S.

Autistic people: processes at the motor level M⇔M, leads to repetitive movements, echolalia.



The *Learning Styles Inventory* is a tool to determine learning style. The tool divides people into 4 types of learners:

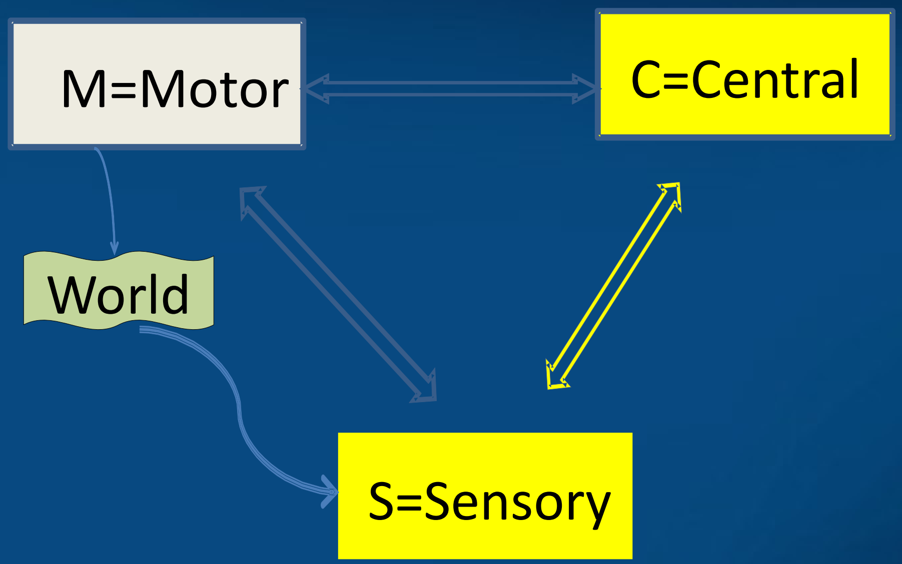
- divergers (concrete, reflective),
- assimilators (abstract, reflective),
- convergers (abstract, active),
- accommodators (concrete, active).

Learning styles D2

Kolb perception-abstraction:
coupling within sensory S⇔S areas, vs.
coupling within central C⇔C areas.

Strong C=>S leads to vivid imagery dominated by sensory experience.

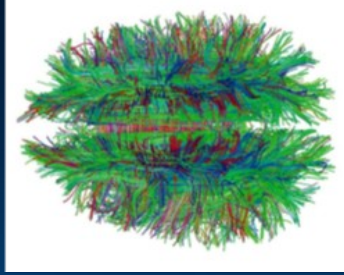
Autism: vivid detailed imagery,
no generalization.



Attention = synchronization of neurons, limited to S, perception S⇔S strongly binds attention => no chance for normal development.

Asperger syndrome strong C=>S activates sensory cortices preventing understanding of metaphoric language.

If central C⇔C processes dominate, no vivid imagery but efficient abstract thinking is expected - mathematicians, logicians, theoretical physicist, theologians and philosophers ideas.



4 styles and more

Assimilators think and watch: prone to abstract thinking, reflective observation, inductive reasoning due to strong connections S=>C and within C⇔C, weak connections from S=>M and C=>M.

Convergers combine abstract conceptualization, active experimentation, using deductive reasoning in problem solving.
Strong C⇔C and C=>M flow of activity.

Divergers focus on concrete experience S⇔S, strong C⇔S connections and C⇔C activity facilitating reflective observation, strong imagery, novel ideas but weak motor activity.

Accommodators have balanced sensory, motor and central processes and thus combine concrete experience with active experimentation supported by central processes S⇔C⇔M.

The idea of learning styles is criticized because there was no theoretical framework behind it, but objective tests of the learning styles may be based on brain activity.

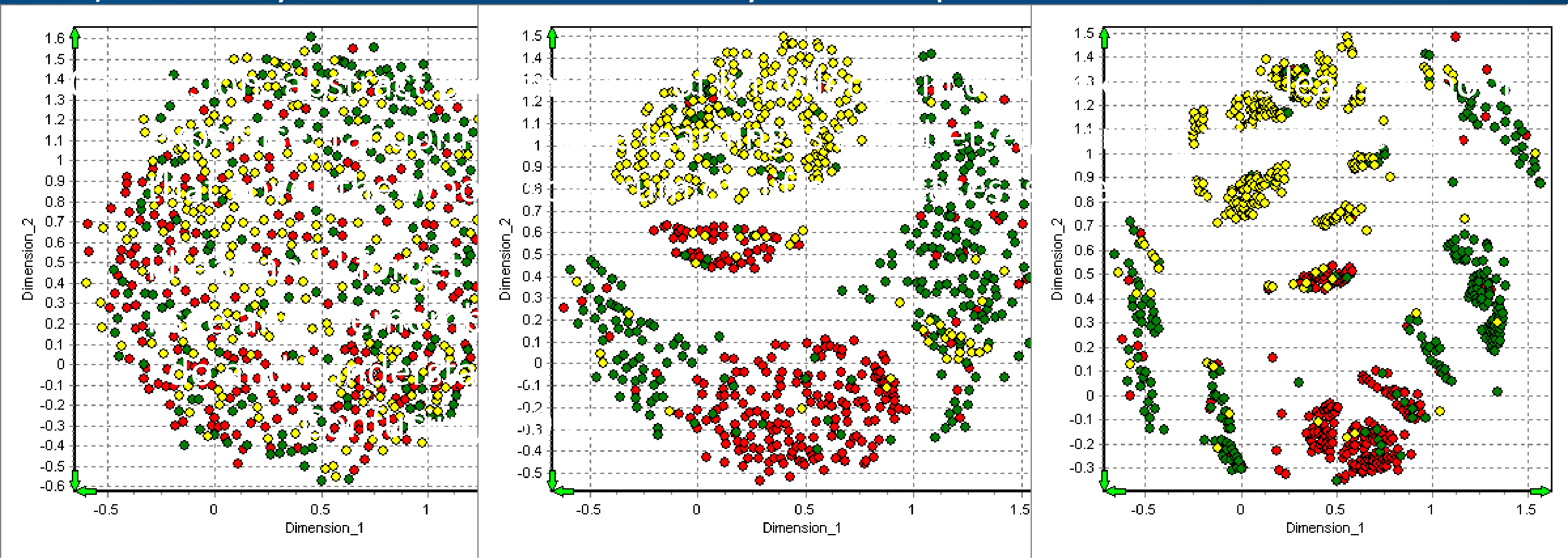
How to become an expert?

Textbook knowledge in medicine: detailed description of all possibilities.

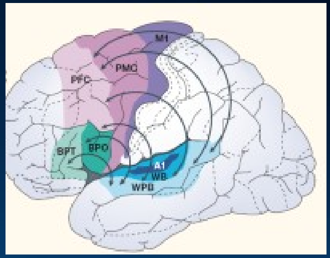
Effect: neural activation flows everywhere and correct diagnosis is impossible.
Correlations between observations forming prototypes are not firmly established.
Expert has only correct, “intuitive” associations.

Example: 3 diseases, vector NLP on clinical case description, MDS visualization.

1) System that has been trained on textbook knowledge.
2) Same system that has learned later on real cases.
3) Same system that has learned only on description of real cases.



Creativity with words



The simplest testable model of creativity (~ Campbell BVSR):

- create interesting novel words that capture some features of products;
- understand new words that cannot be found in the dictionary.

Model inspired by the putative brain processes when new words are being invented starting from some keywords priming auditory cortex.

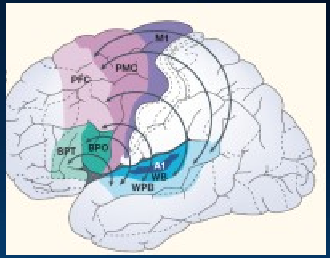
Phonemes (allophones) are resonances, ordered activation of phonemes will activate both known words as well as their combinations; context + inhibition in the winner-takes-most leaves only a few candidate words.

Creativity = network+imagination (fluctuations)+filtering (competition)

Imagination: chains of phonemes activate both word and non-word representations, depending on the strength of the synaptic connections. **Filtering**: based on associations, emotions, phonological/semantic density.

discoverity = {disc, disco, discover, verity} (discovery, creativity, verity)
digventure ={dig, digital, venture, adventure}   new!
Visual: Google Deep Dream hallucinations – but video streams not natural.

Creativity with words



The simple

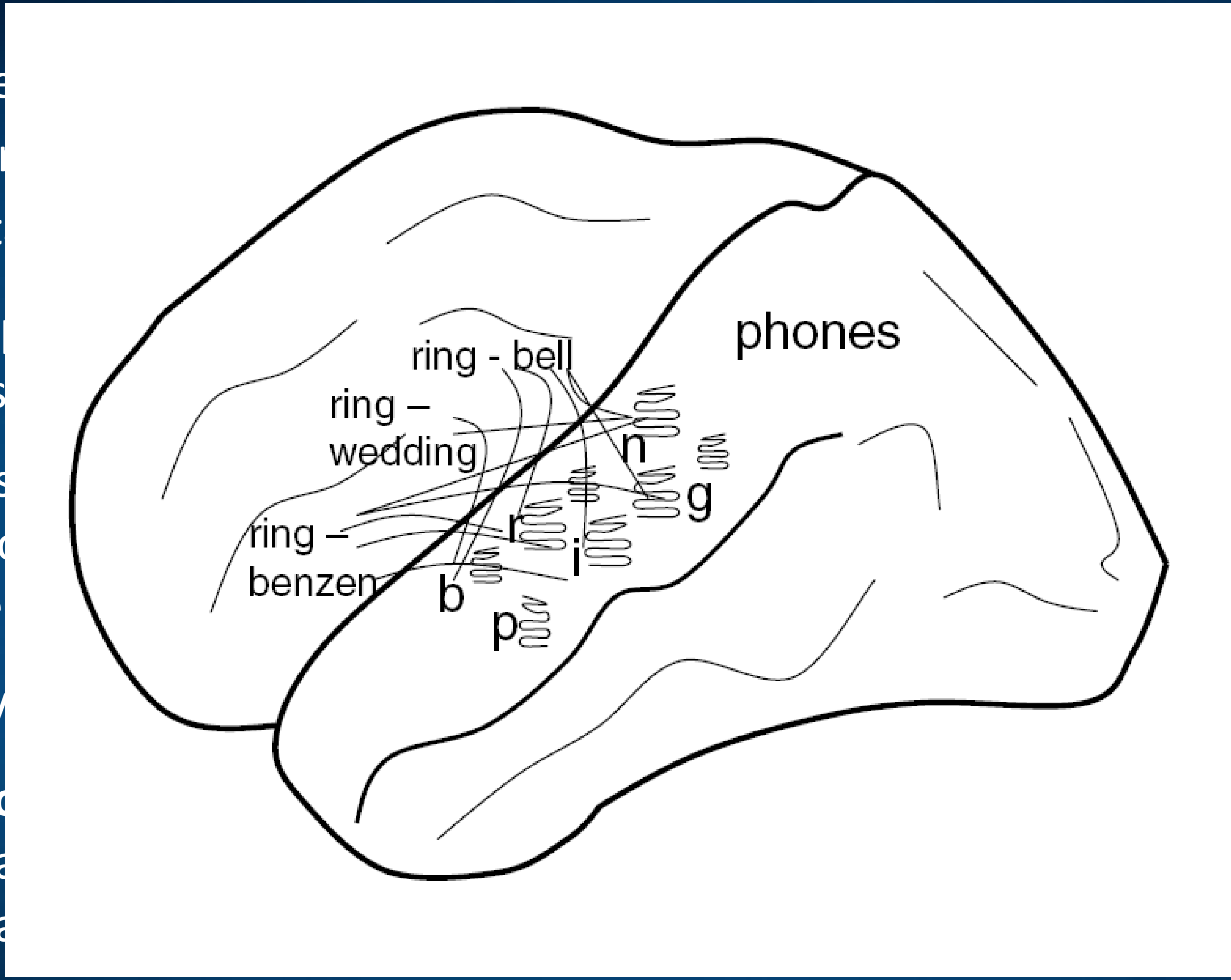
- create i... ducts;
- underst...

Model ins... being invented s...

Phonemes... emes will activate b... inhibition in the winne...

Creativity... petition)

Imaginatio... representa... ions. **Filtering**: based on a...



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Conspiracy in the brain

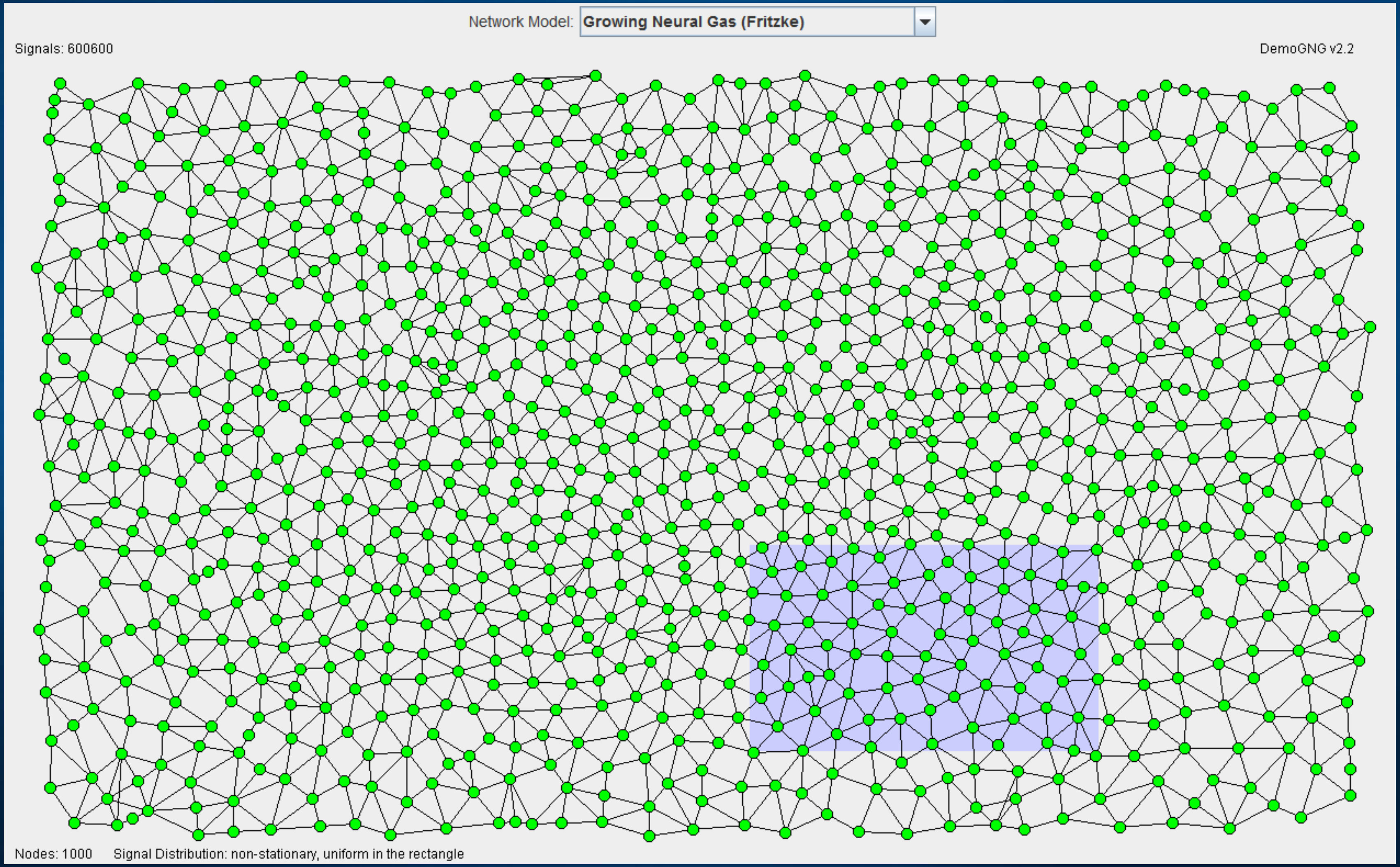
- Emotional situations => neurotransmitters => neuroplasticity => fast learning, must be important.
- Fast learning => high probability of wrong interpretation.
- Traumatic experiences, hopelessness, decrease brain plasticity and leave only strongest association.
- Conspiracy theories form around associations with frozen brain activities, that become strong attractors channeling thoughts.

- Simple associations save brain energy and rational arguments cannot change them.
- This explanation becomes so obviously obvious …

Model: concept vectors derived from a corpus + MDS or Growing Neural Gas visualization (Martinetz & Schulten, 1991).

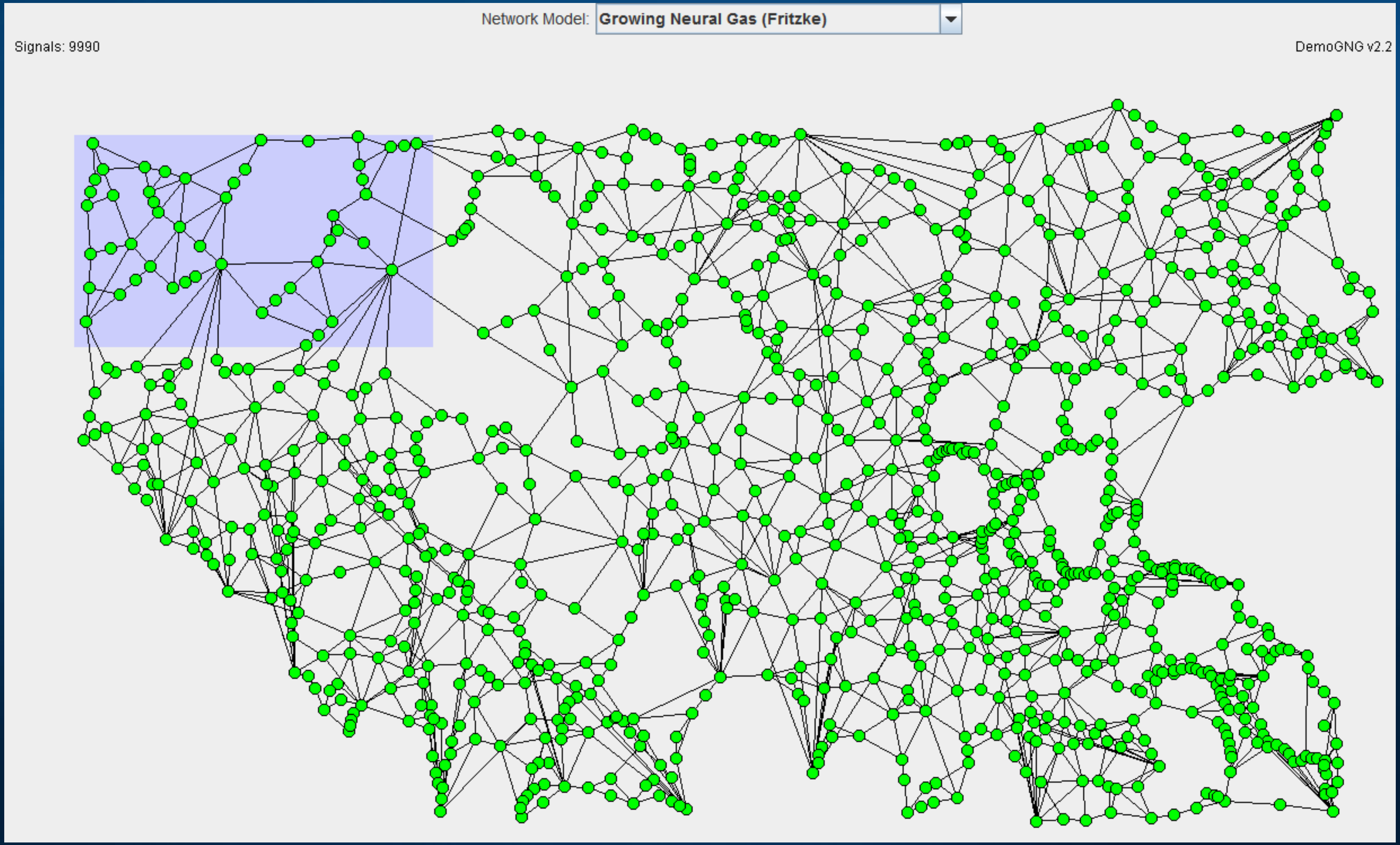
Internalization of environment

Episodes are remembered and serve as reference points, if observations are unbiased they reflect reality, creating correct associations.



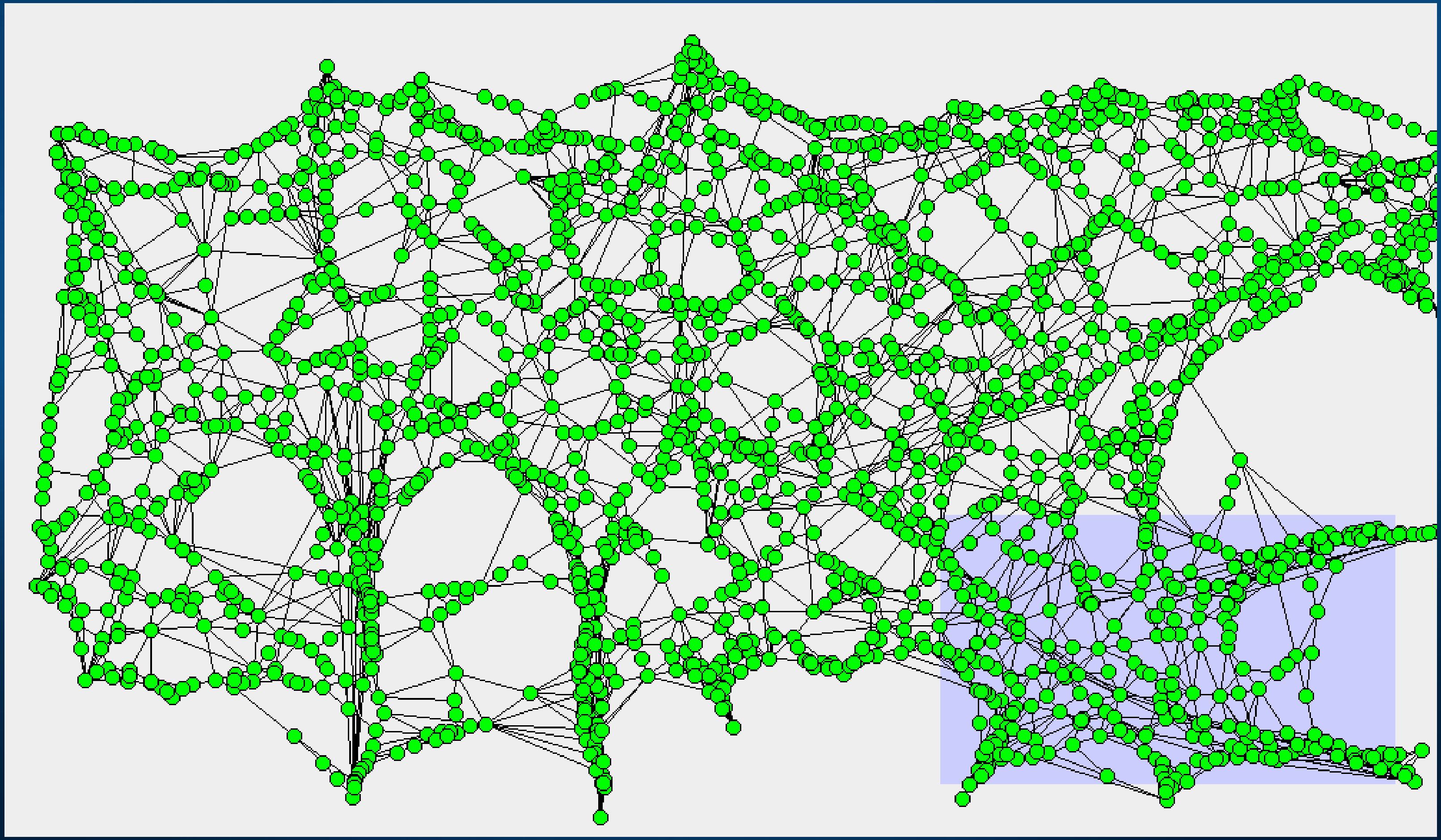
Extreme plasticity

Brain plasticity (learning) is increased if long, Slow strong emotions are involved. Followed by depressive mood it leads to severe distortions, false associations, simplistic understanding.



Conspiracy views

Illuminati, masons, Jews, UFOs, or twisted view of the world leaves big holes and admits simple explanations that save mental energy, creating „sinks" that attract many unrelated episodes.

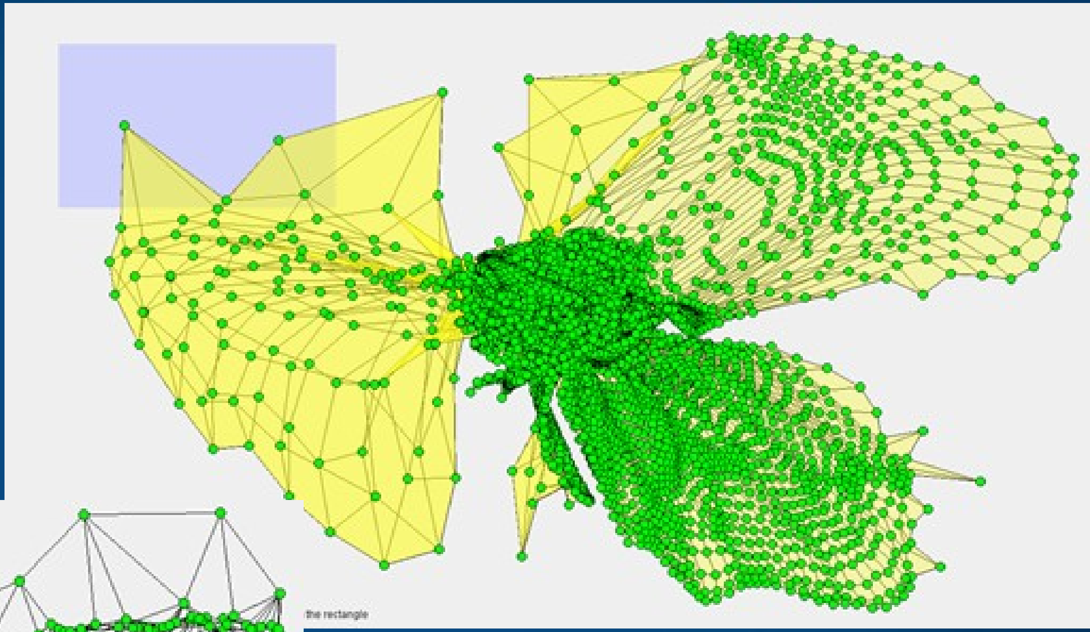


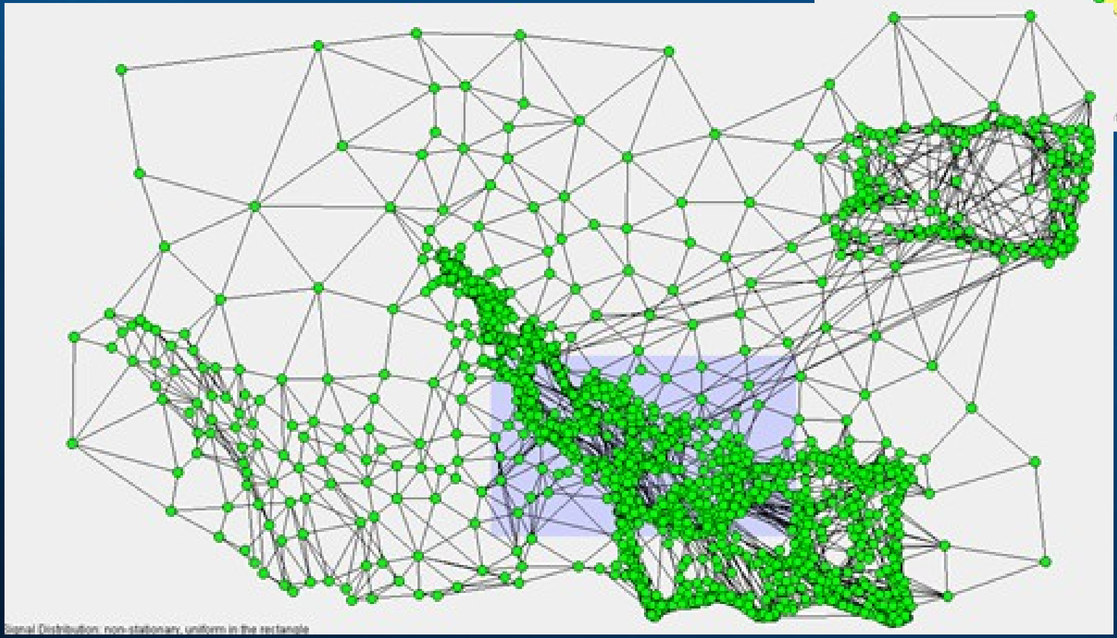
Memoids …

Totally distorted world view, mind changed into a memplex

…

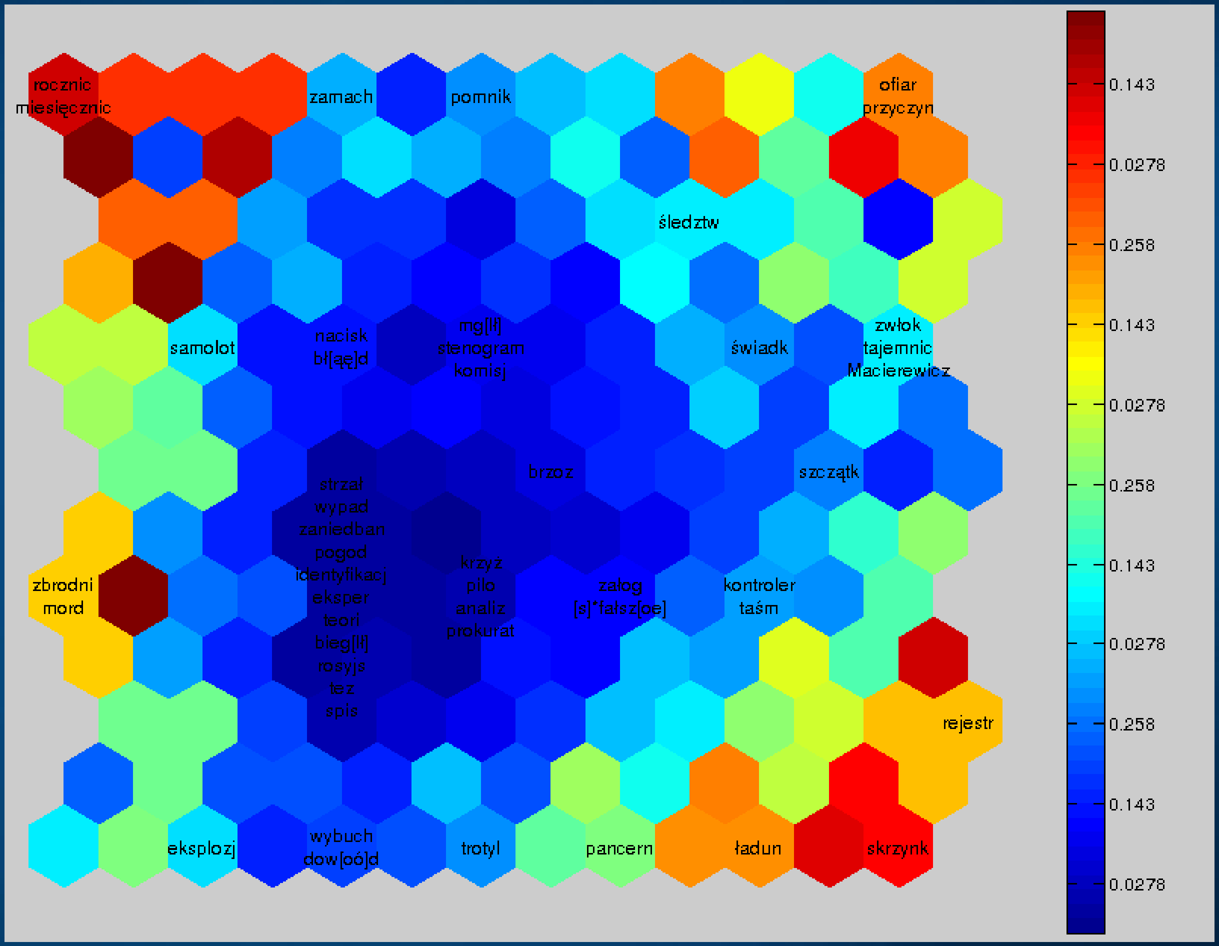
Ready for sacrifice.





SOM on real newspaper data

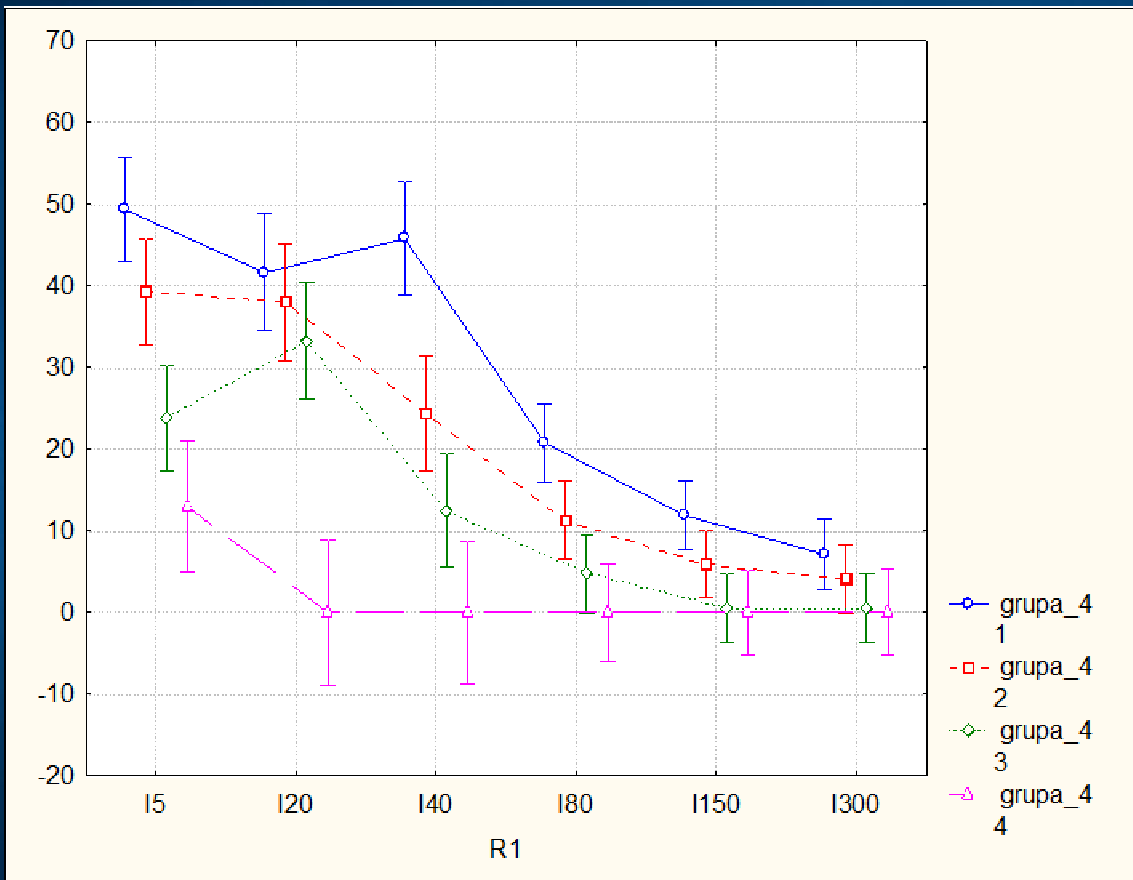
Different groups of people read different newspapers, are exposed to different media and social networks, resulting in different network of concepts and sharp polarization of opinions.

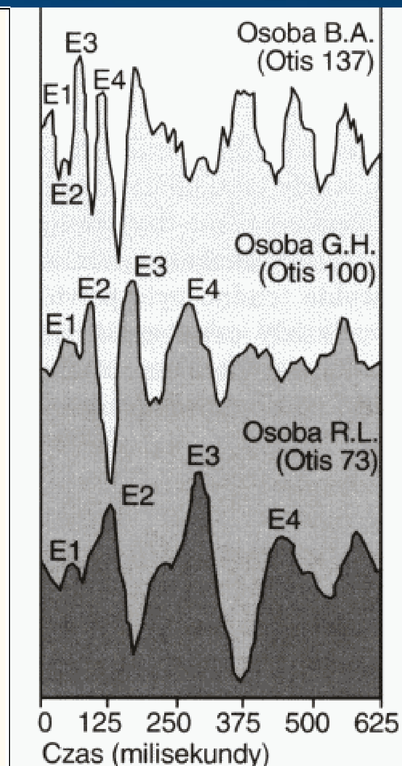


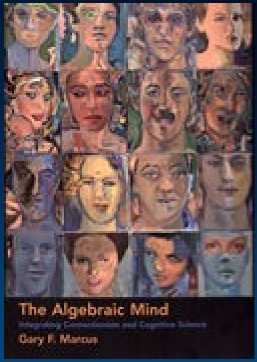
Big sinks attract neurodynamics manifesting in strong automatic associations with core concepts.

Work in progress (with J. Szymanski et al.)

Abstract thinking







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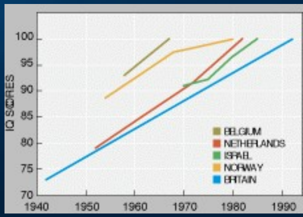
brains?



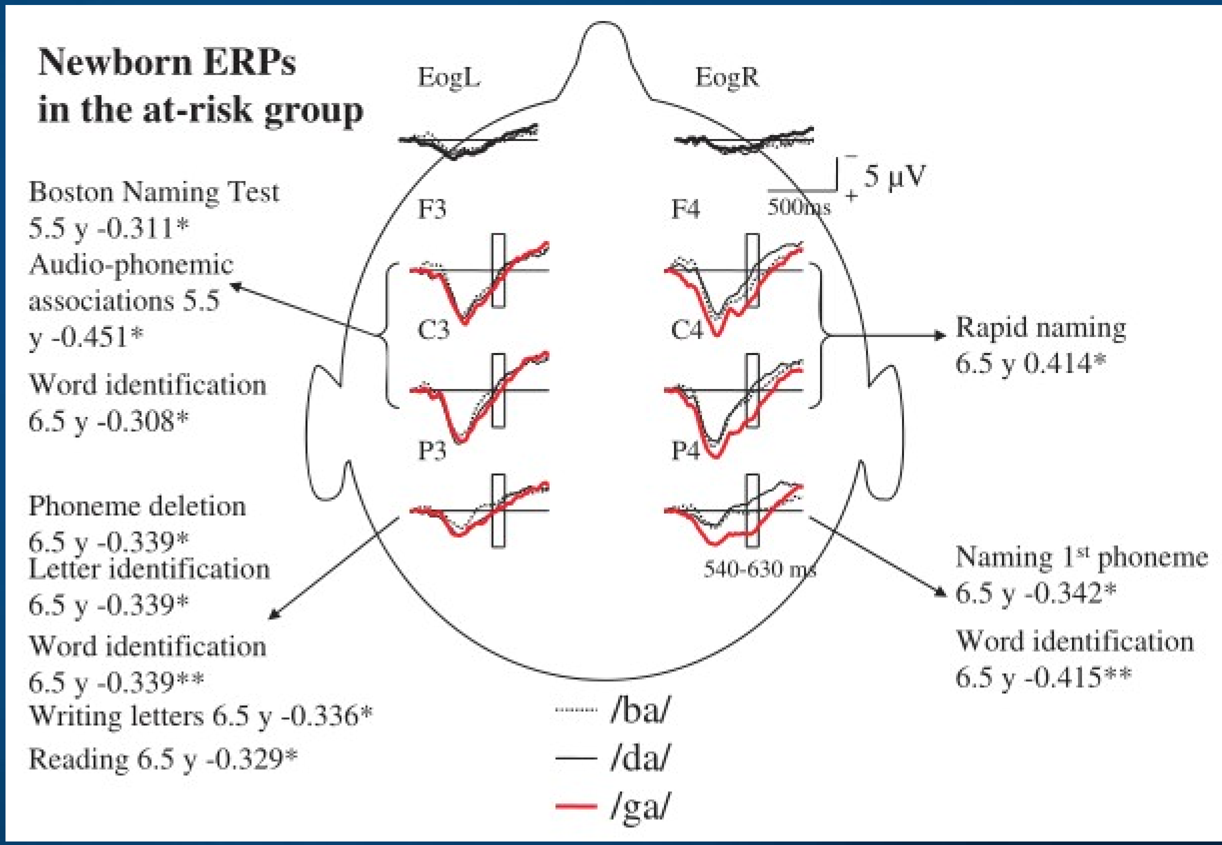
Infants, syllables

Brains of newborns react to ba/ga/da syllables in the 3–5 day of life in a way that allows for prediction of problems with learning to read years later.

(D. Molfesse, 2000).

Can we change it by training infants?

We hope so, this may be verified using ERPs.



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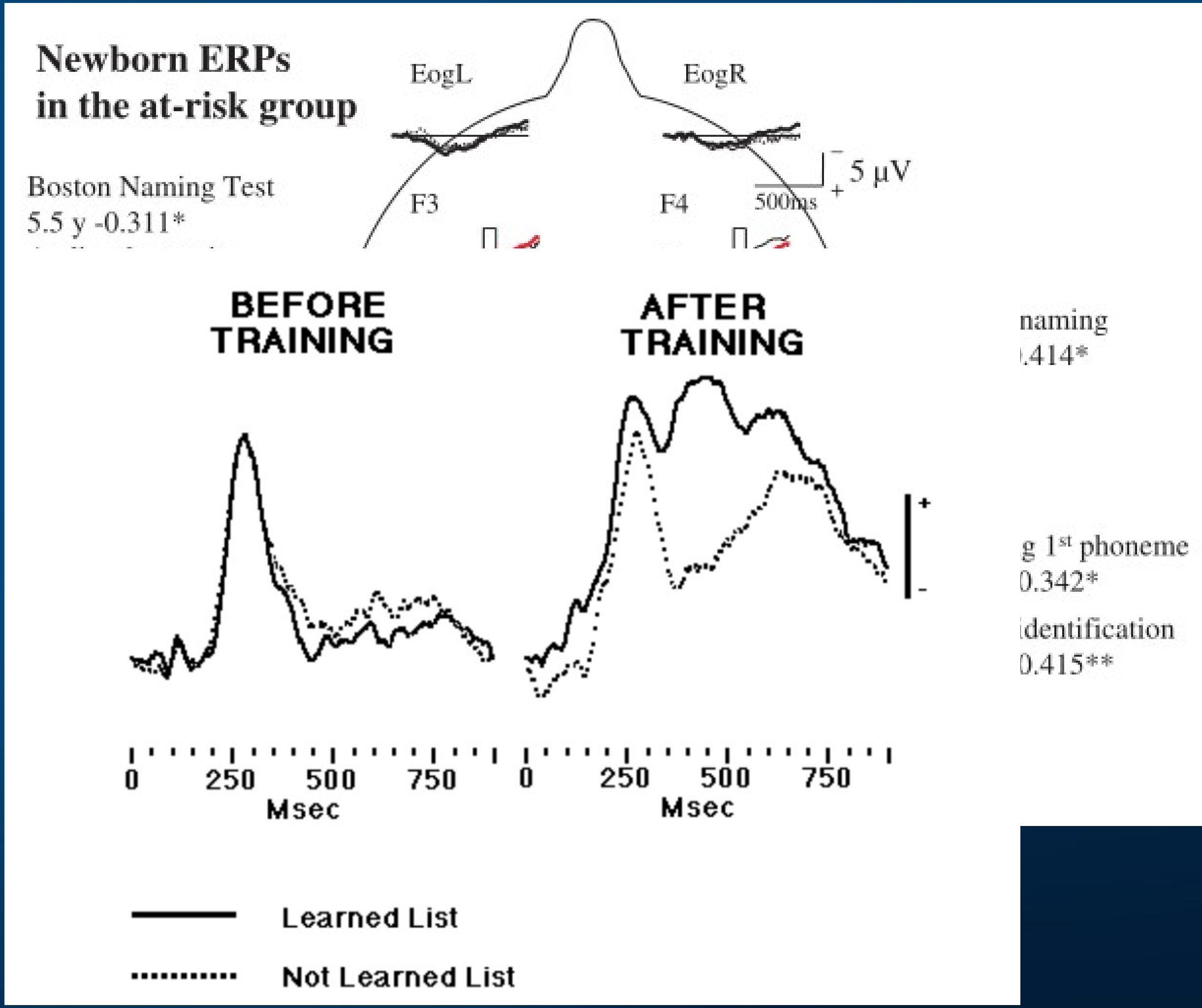
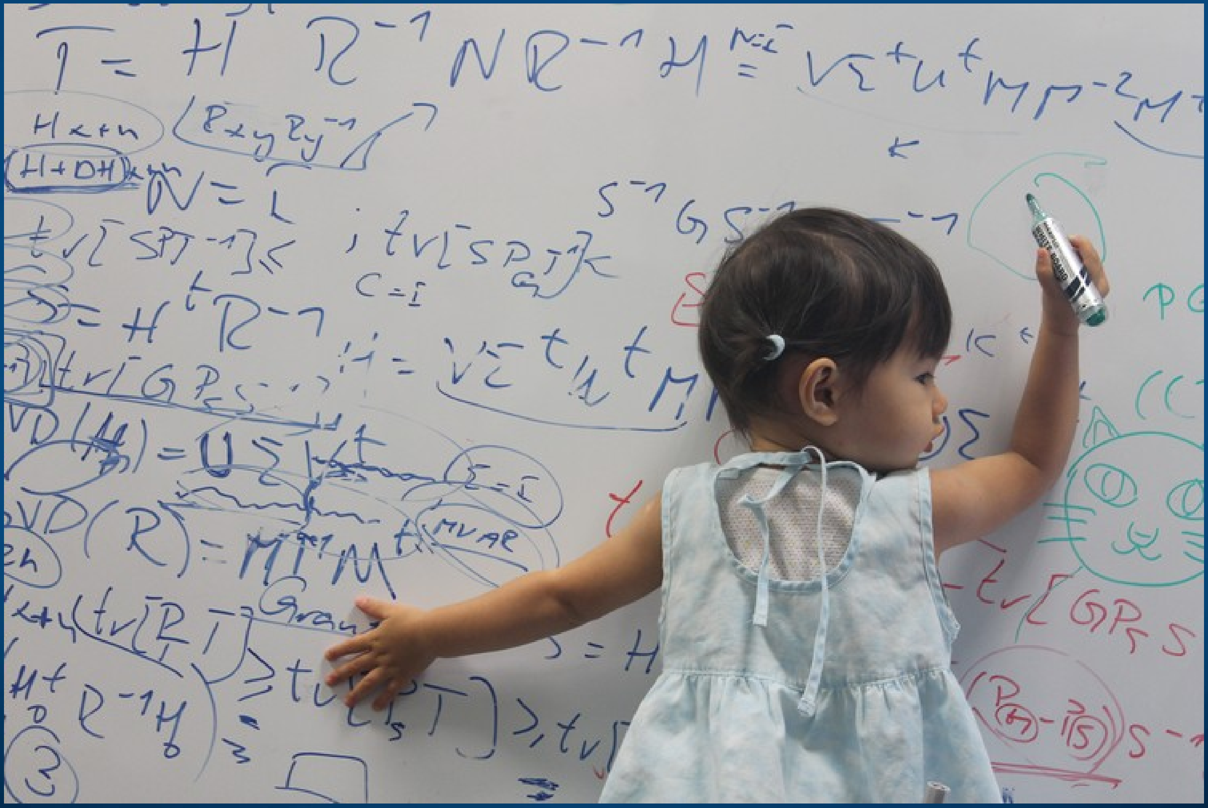


BabyLab in Neurocognitive Laboratory

CMIT NCU



Dyscalculia screening/therapy

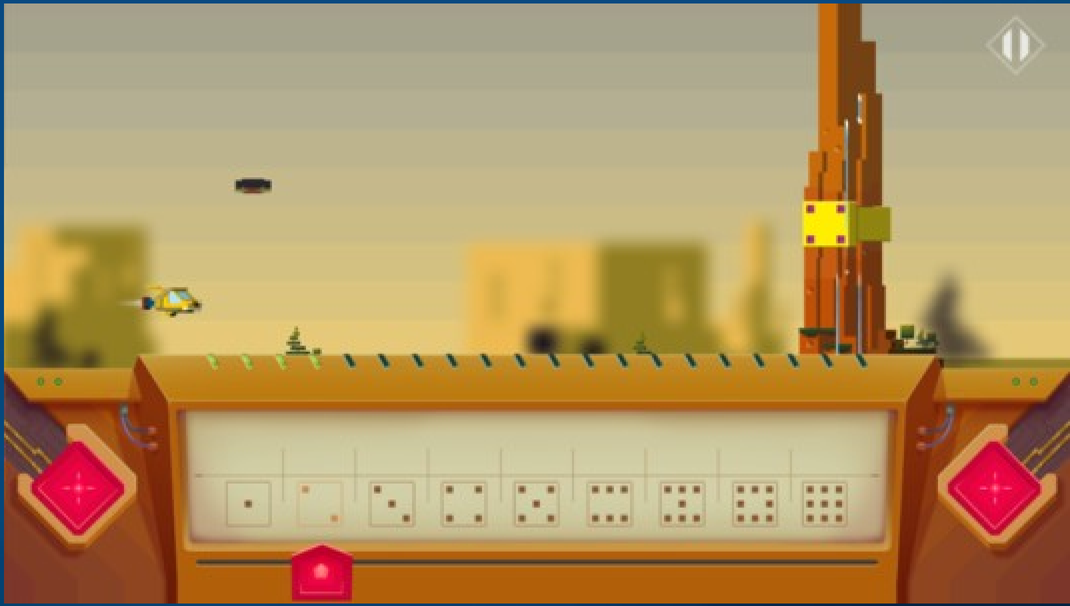
Understanding numerosity, a new complex brain function, involves HIPS structure. **6-10%** of children in primary education suffer from dyscalculia, specific difficulties with learning mathematical concepts. Rarely diagnosed, most countries have no screening tests.

Goals:

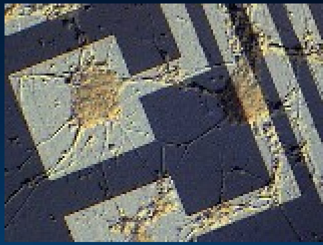
1. Introduce screening test for the preschool/first class to identify children with the risk of dyscalculia.

2. Short intensive training using computer game to associate mental number line with spatial dimensions.

Further therapy is done by experts.



The Great Artificial Brain Race



BLUE BRAIN, HBP**:** École Polytechnique Fédérale de Lausanne, in Switzerland, use an IBM supercomputer to simulate minicolumn.

C2: 2009 IBM Almaden built a cortical simulator on Dawn, a Blue Gene/P supercomputer at Lawrence Livermore National Lab. C2 simulator re-creates 10^9 neurons connected by 10^{13} synapses, small mammal brain.

NEUROGRID: Stanford (K. Boahen), developing chip for ~ 10^6 neurons and ~ 10^{10} synapses, aiming at artificial retinas for the blind.

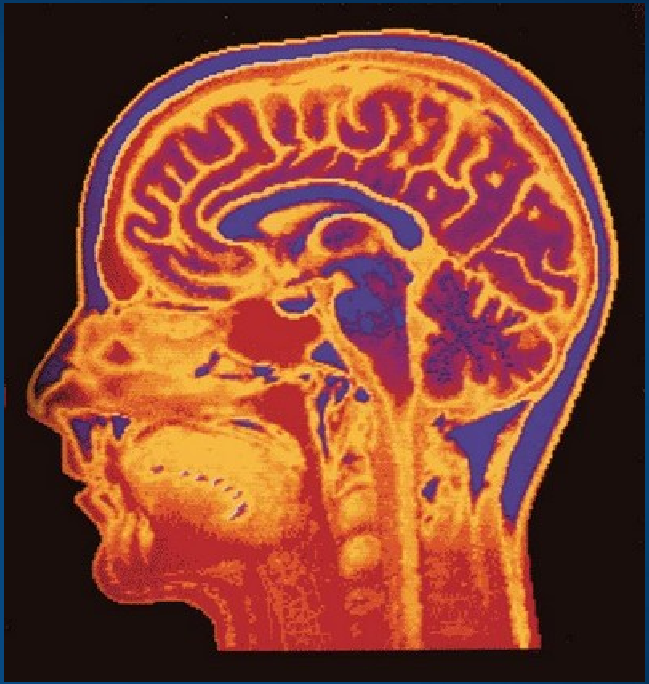
IFAT 4G: Johns Hopkins Uni (R.Etienne-Cummings) Integrate and Fire Array Transceiver, over 60K neurons with 120M connections, visual cortex model.

Brain Corporation: San Diego (E. Izhakievich), neuromorphic vision.

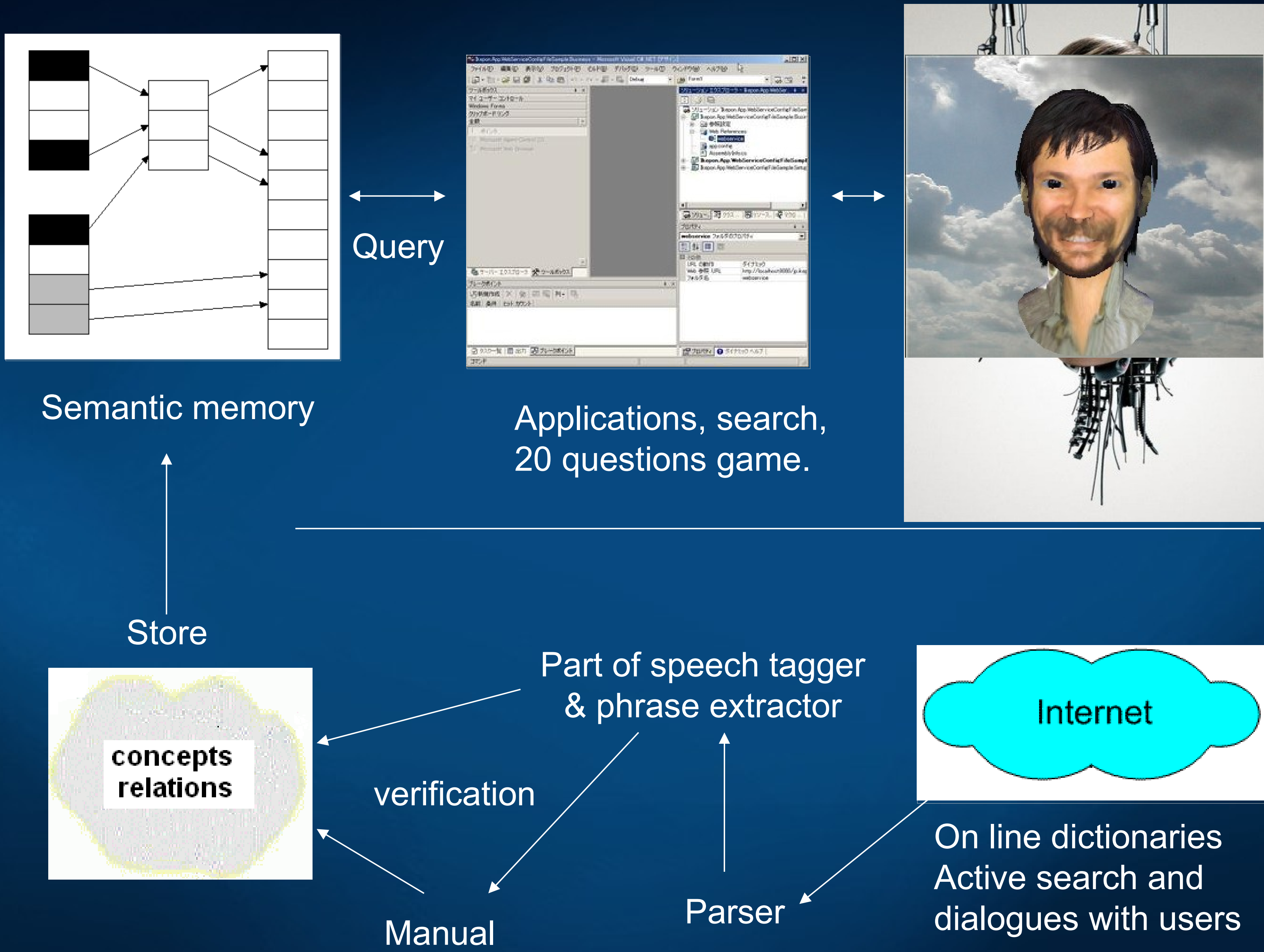
BRAINSCALES: EU neuromorphic chip project, FACETS, Fast Analog Computing with Emergent Transient States, now BrainScaleS, complex neuron model ~16K synaptic inputs/neuron, integrated closed loop network-of-networks mimicking a distributed hierarchy of sensory, decision and motor cortical areas, linking perception to action.

Understanding by creating brains

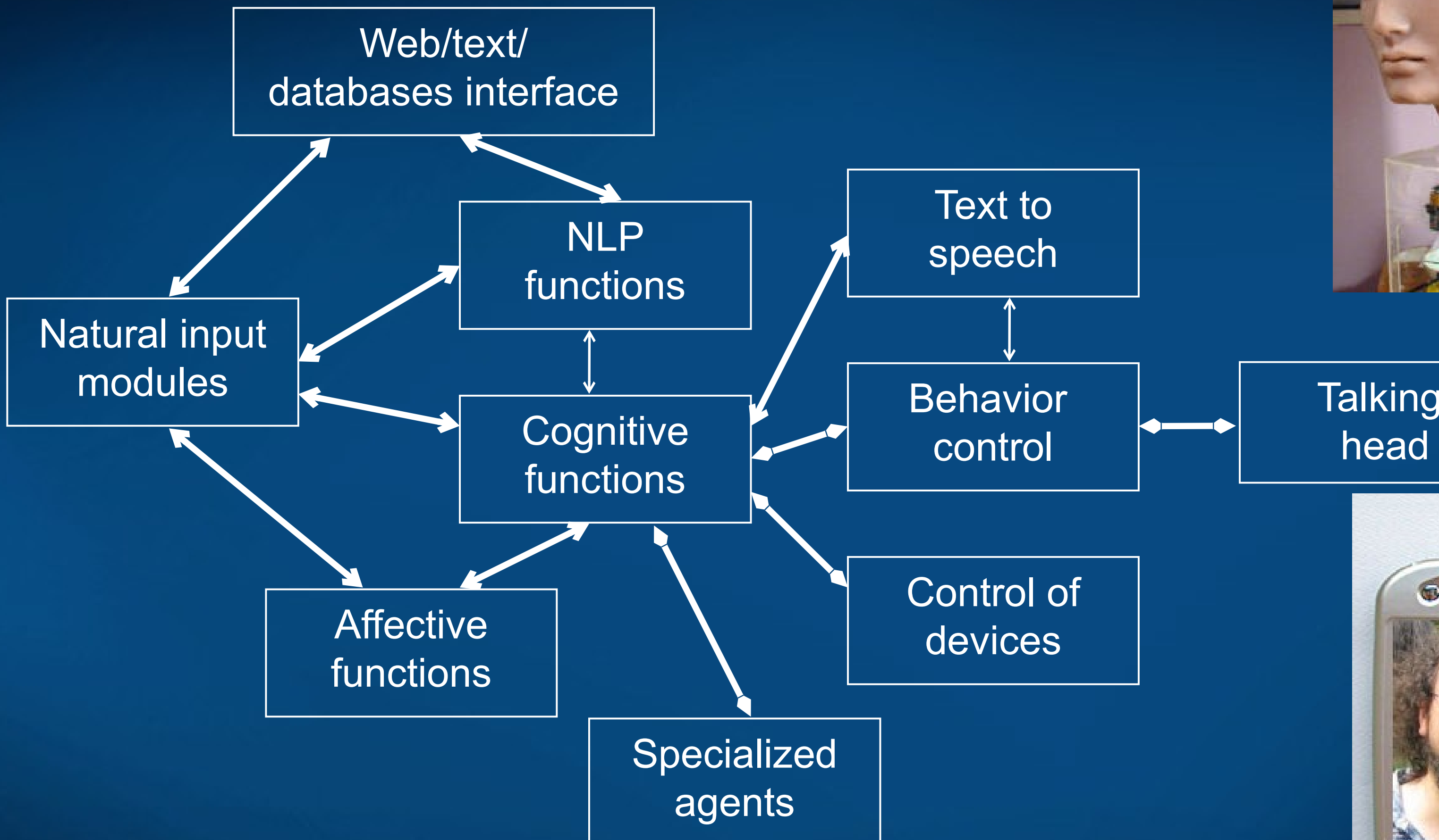
- "Here, we aim to understand the brain to the extent that we can make humanoid robots solve tasks typically solved by the human brain by essentially the same principles. I postulate that this 'Understanding the Brain by Creating the Brain' approach is the only way to fully understand neural mechanisms in a rigorous sense."



- M. Kawato, From 'Understanding the Brain by Creating the Brain' towards manipulative neuroscience.
  Phil. Trans. R. Soc. B 27 June 2008 vol. 363 no. 1500, pp. 2201-2214
- Humanoid robot may be used for exploring and examining neuroscience theories about human brain.
- Engineering goal: build artificial devices at the brain level of competence.

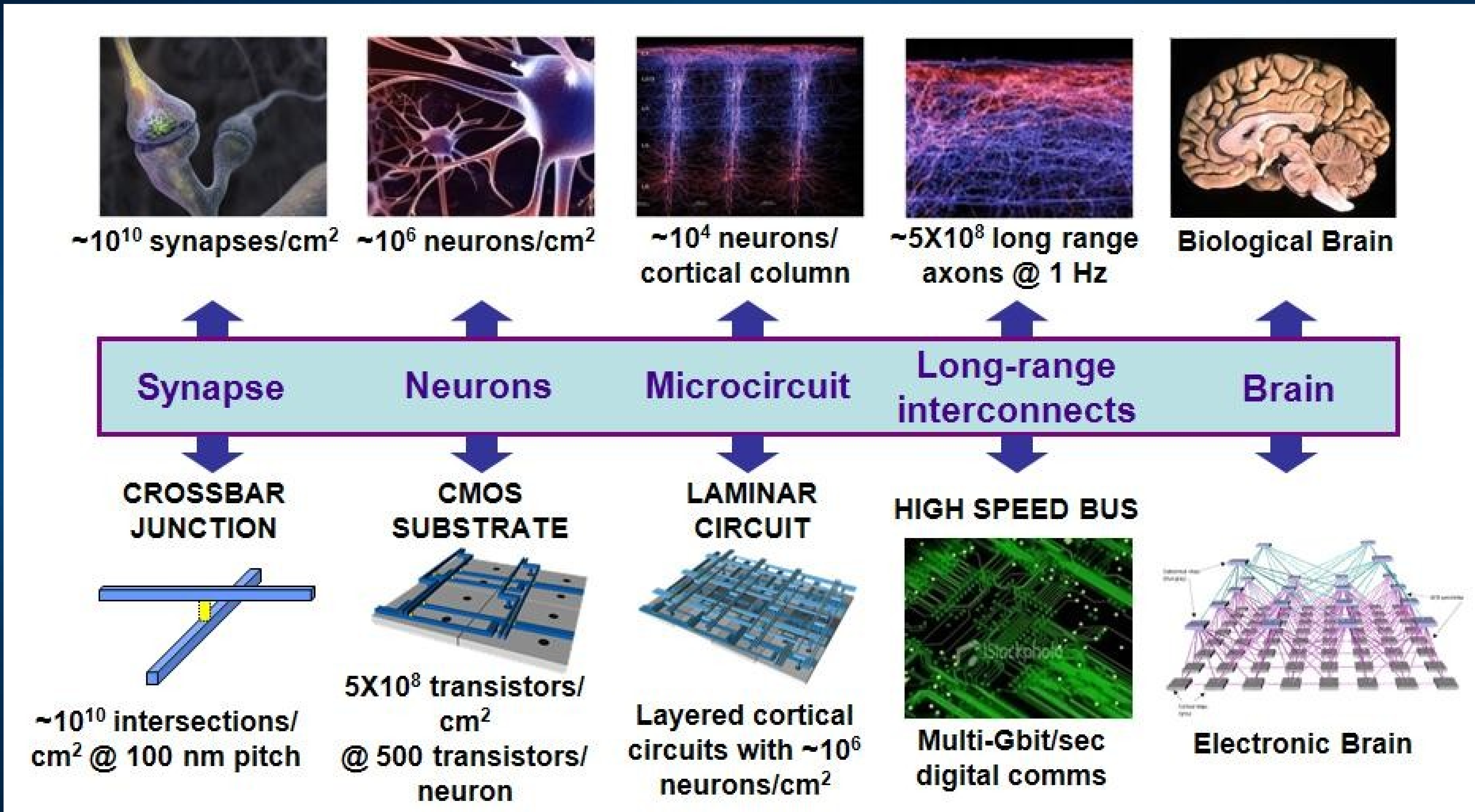

Query
Semantic memory
Applications, search,
20 questions game.
Store
Part of speech tagger
& phrase extractor
Internet
concepts
relations
verification
On line dictionaries
Active search and
dialogues with users
Parser
Manual

DREAM top-level architecture



DREAM project, focused on perception (visual, auditory, text inputs), cognitive functions (reasoning based on perceptions), natural language communication in well defined contexts, real time control of the simulated/physical head.

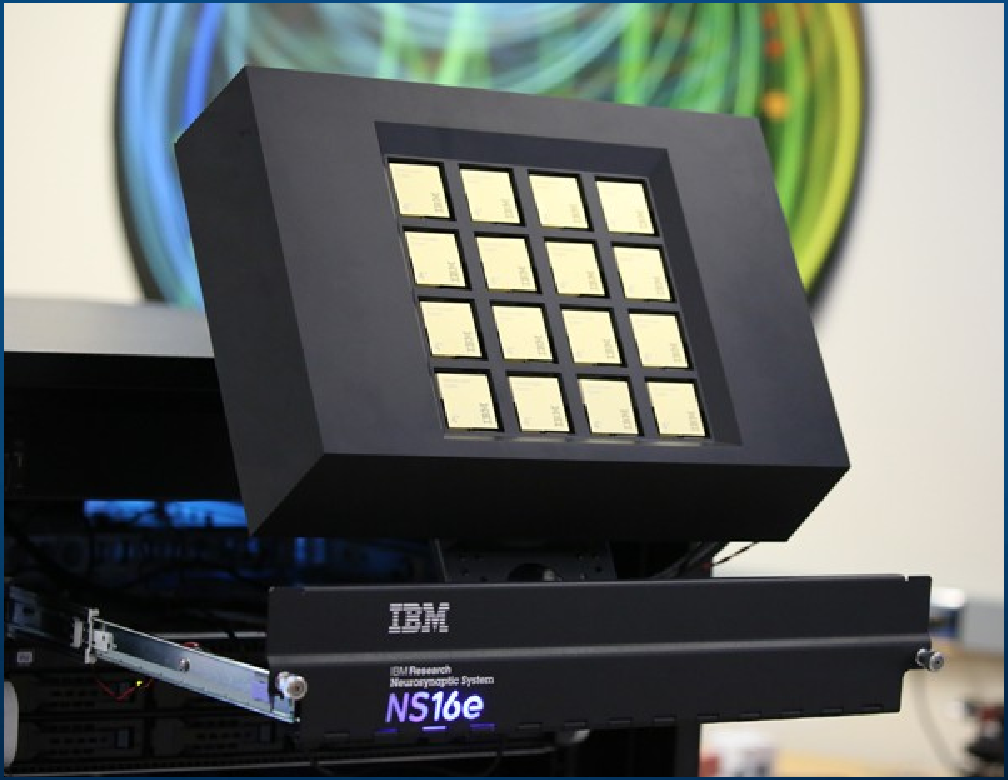
From brains to machines



Source: DARPA Synapse project

Neuromorphic computers

Synapse 2015: IBM TrueNorth chip
~1M neurons and ¼G synapses, ok 5.4G tranzystorów.
NS16e module=16 chips=16M neurons, >4G synapses, requires only 1.1 W!
Scaling: 256 modules, ~4G neurons, ~1T= 10^{12} synapses <300 W power!
IBM Neuromorphic System can reach complexity of the human brain.



Few Initiatives

IEEE Computational Intelligence Society Task Force (J. Mandziuk & W. Duch), **Towards Human-like Intelligence.**

IEEE SSCI The 4th IEEE Symposium on Computational Intelligence for Human-like Intelligence, Athens, Greece, 6-9.12.2016.

World Congress of Computational Intelligence 2014, Special Session: Towards Human-like Intelligence (A-H Tan, J. Mandziuk, W .Duch)

Brain-Mind Institute Schools, International Conference on Brain-Mind (ICBM) and Brain-Mind Magazine (Juyang Weng, Michigan SU).

AGI: conference, Journal of Artificial General Intelligence comments on Cognitive Architectures and Autonomy: A Comparative Review (eds. Tan, Franklin, Duch).

BICA: Annual International Conf. on Biologically Inspired Cognitive Architectures, 3rd Annual Meeting of the BICA Society, Palermo, Italy, 31.10- 3.11.2012

Conclusions

Grand challenges

are facing phenomics

at every level!

But is there a shorter route
to understand human behavior?

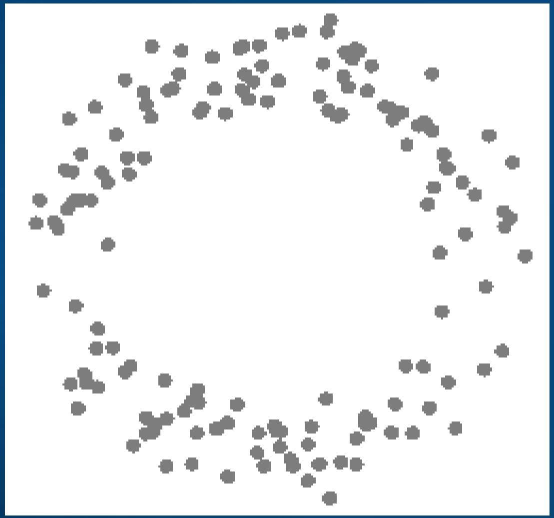
I do not think so …

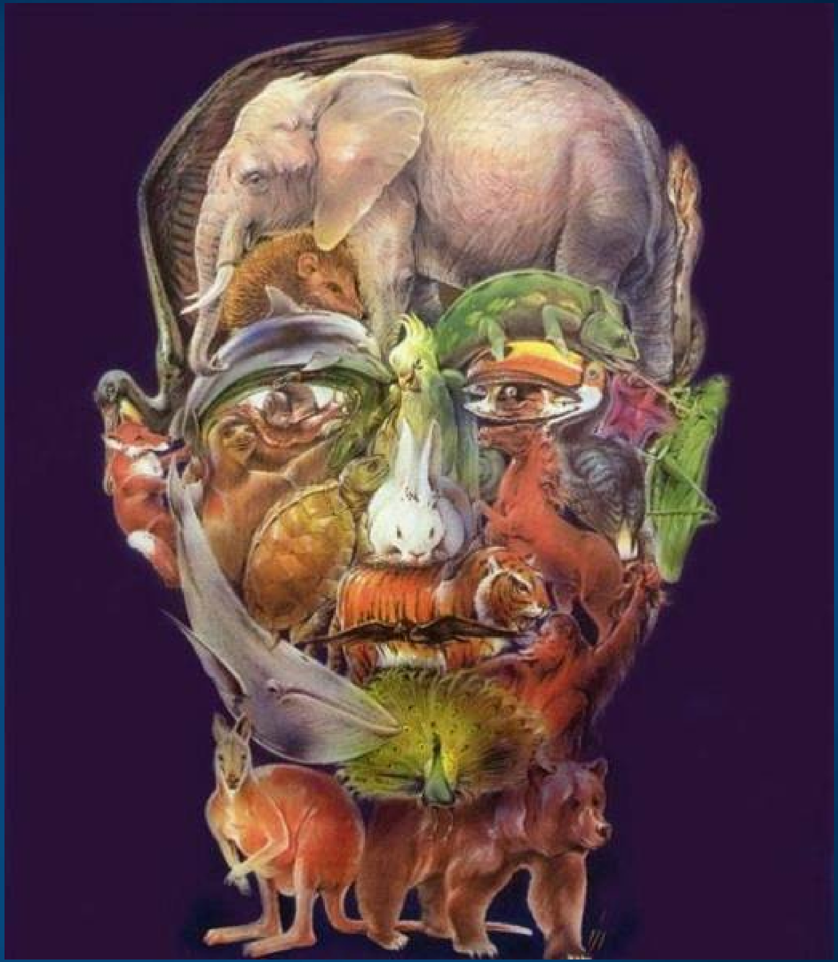
Neurodynamics will be the key.

Duch W, *Brains and Education: Towards Neurocognitive Phenomics* (2013)

Soul or brain: what makes us human? Interdisciplinary Workshop, Torun 19-21.10.2016

Thank you for synchronization of your neurons!





Google: Wlodzislaw Duch
=> papers, talks, lectures …

DREAM/HIT – larger view …