Multi-level explanations in neuroscience I: From genes to subjective experiences.

Włodzisław Duch

Neurocognitive Laboratory,
Center of Modern Interdisciplinary Technologies,
Dept. of Informatics, Faculty of Physics, Astronomy & Informatics,
Nicolaus Copernicus University

Google: W. Duch

BRANDY, 26-27 June, Val del Sol
On the threshold of a dream ... (50 y!)

How subjective mental states arise from specific activity of the brain networks?

- Mind/Brain at many levels.
- Global brain initiatives.
- Human enhancement or why is this important
- Brain networks.
- Decoding Mental States.
- Neurodynamics.
- Final words.

Ultimate goal: Optimize/repair your brain!

Mind/brain at many levels
Brains ⇔ Minds

Define mapping $S(M) \Leftrightarrow S(B)$, as in BCI.
How do we describe the state of mind?
Verbal description is not sufficient unless words are represented in a space with dimensions that measure different aspects of experience.
Stream of mental states, movement of thoughts $\Leftrightarrow$ trajectories in psychological spaces.

**Two problems**: discretization of continuous processes for symbolic models, and lack of good phenomenology – we are not able to describe our mental states.

Neurodynamics: bioelectrical activity of the brain, neural activity measured using EEG, MEG, NIRS-OT, PET, fMRI ...

2008: The Consortium for Neuropsychiatric Phenomics

“... categories, based upon presenting signs and symptoms, may not capture fundamental underlying mechanisms of dysfunction” (Insel et al., 2010).

New approach: RDOC NIMH.

Description of organisms at different levels will help to answer different types of questions. Network level is in the middle and can be connected to the mental level via computational models.
NIMH RDoC Matrix for deregulation of 5 large brain systems.

Psychological constructs are necessary to talk about mental states.

How are they related to physical processes?
Lewin’s psychological forces

Kurt Lewin, founder of social psychology, analyzed interactions between people and their environment creating psychology inspired by field theory. Transitions between mental states = psychological forces. Regions of positive valence are in basins of attractors of neurodynamics.

K. Lewin books: *Principles of Topological Psychology* (1936);
*Conceptual Representation & Measurement of Psychological Forces* (1938);
*Field Theory in Social Science* (1951).
NIMH RDoC Matrix for deregulation of 6 large brain systems.
Instead of classification of mental disease by symptoms use **Research Domain Criteria (RDoC)** based on multi-level neuropsychiatric phenomics.

1. **Negative Valence Systems**, primarily responsible for responses to aversive situations or context, such as fear, anxiety, and loss.

2. **Positive Valence Systems** are primarily responsible for responses to positive motivational situations or contexts, such as reward seeking, consummatory behavior, and reward/habit learning.

3. **Cognitive Systems** are responsible for various cognitive processes.

4. **Social Processes Systems** mediate responses in interpersonal settings of various types, including perception and interpretation of others’ actions.

5. **Arousal/Regulatory Systems** - generating activation of neural systems in various contexts, homeostatic regulation, energy balance and sleep.

6. **Sensorimotor systems** responsible for the control and execution of motor behaviors, and their refinement during learning and development.
Multi-level phenomics

Research Domain Criteria (RDoC) matrix is based on multi-level neuropsychiatric phenomics describing large brain systems deregulation, but links to behavior should be analyzed at the network level, where specialized functions are implemented. In AI:

M. Minsky, Society of mind (1986)

Decompose brain network dynamics into meaningful components of activity related to various brain functions.

Include influence of genes, molecules, cells, circuits, physiology, behavior, self-reports on network functions.
<table>
<thead>
<tr>
<th>Construct/Subconstruct</th>
<th>Genes</th>
<th>Molecules</th>
<th>Cells</th>
<th>Circuits</th>
<th>Physiology</th>
<th>Behavior</th>
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<tbody>
<tr>
<td><strong>Perception</strong></td>
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<td>Attention</td>
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<td>Auditory Perception</td>
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<td>Elements</td>
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<tr>
<td>Olfactory/Somatosensory/Multimodal/Perception</td>
<td>Elements</td>
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<td><strong>Declarative Memory</strong></td>
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<tr>
<td><strong>Language</strong></td>
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<td><strong>Cognitive Control</strong></td>
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<td>Goal Selection; Updating, Representation, and Maintenance</td>
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<td>Focus 1 of 2 → Goal Selection</td>
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<td>Focus 2 of 2 → Updating, Representation, and Maintenance</td>
<td>Elements</td>
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<tr>
<td>Response Selection; Inhibition/Suppression</td>
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<td>Focus 1 of 2 → Response Selection</td>
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Global Brain Initiatives
or why is this so important?
Costs of brain diseases


179 million, or 1/3 of all European citizens, had at least one brain disorder. 45% of the total annual health budget of Europe!

Total cost of brain disorders in EU estimated in 2010: 798 billion €/year, average direct health care costs represent 37%, direct nonmedical costs 23%, and indirect costs 40%.

China: >20% of population (~250 mln) suffering from some mental disorder.

Total costs of disorders of the brain in Poland, 2010 estimates.

<table>
<thead>
<tr>
<th>Disorder</th>
<th># people</th>
<th>mln €</th>
</tr>
</thead>
<tbody>
<tr>
<td>Addiction</td>
<td>1 201</td>
<td>2 501</td>
</tr>
<tr>
<td>Anxiety</td>
<td>5 261</td>
<td>2 882</td>
</tr>
<tr>
<td>Dementia</td>
<td>358</td>
<td>2 480</td>
</tr>
<tr>
<td>Epilepsy</td>
<td>298</td>
<td>745</td>
</tr>
<tr>
<td>Headache</td>
<td>12 025</td>
<td>1 559</td>
</tr>
<tr>
<td>Mood</td>
<td>2 499</td>
<td>4 489</td>
</tr>
<tr>
<td>Psychotic</td>
<td>371</td>
<td>3 723</td>
</tr>
<tr>
<td>Stroke</td>
<td>503</td>
<td>2 187</td>
</tr>
</tbody>
</table>

International Brain Initiatives

- Canadian Brain Research Strategy
- U.S. BRAIN Initiative
- European Union Human Brain Project
- China Brain Project

“Develop new technologies to explore how the brain’s cells and circuits interact at the speed of thought, ultimately uncovering the complex links between brain function and behavior. Explore how the brain records, processes, uses, stores, and retrieves vast quantities of information. Help bring safe and effective products to patients and consumers.”

Since 2013 numerous exciting developments in neurotechnology and our understanding of the brain have been made by scientists across the globe.
The mission of IEEE Brain is to facilitate cross-disciplinary collaboration and coordination to advance research, standardization and development of technologies in neuroscience to help improve the human condition.

20 IEEE Societies are involved, including:

**IEEE Computational Intelligence Society**; Computer Society; Consumer Electronics Society; Digital Senses Initiative; Robotics and Automation Society; Sensors Council; Signal Processing Society; Society on Social Implications of Technology; **Systems, Man, and Cybernetics Society**, International Neuroethics Society, and a few other societies.

Most these societies are also involved in artificial intelligence.

**Satya Nadella (CEO, Microsoft)**: to celebrate National Disability Employment Awareness Month, I’m sharing examples of how technology can be applied to empower the more than one billion people with disabilities around the world.
Part of the Brain-Machines Interface Workshop and SMC2018.

The IEEE SMC Society and the IEEE President, James Jefferies, are proud to invite you on to a special meeting of **Global Current and Emerging Brain Initiative leaders** and representatives from other groups working on large-scale multi-year brain projects from Australia, Canada, China, Europe (HBP), Japan, Korea, New Zealand, **Poland**, Russia, and US (NSF and NIH), with representatives from the **IEEE Brain Initiative**, International Neuroethics Society, industry, and other stakeholders.

IEEE welcomes collaborative discussions with all stakeholders to better align and integrate IEEE with other existing brain efforts.
Neuroscience => AI


**Artificial neural networks** – simple inspirations, but led to many applications.


**AI Systems inspired by Neural Models of Behavior:**
(A) **Visual attention**, foveal locations for multiresolution “retinal” representation, prediction of next location to attend to.
(B) **Complementary learning systems** and episodic control: fast learning hippocampal system and parametric slow-learning neocortical system.
(C) Models of **working memory** and the Neural Turing Machine.
(D) Neurobiological models of **synaptic consolidation** and the elastic weight consolidation (EWC) algorithm.
Understanding the brain from engineering perspective means to build a model of the brain showing similar functions.

Cognitive informatics, Neurocognitive Informatics.

BICA = Brain Inspired Cognitive Architecture.

Review: Duch, Oentaryo, Pasquier, Cognitive architectures: where do we go from here? 2008
• ORNL, since 1943 as part of the Manhattan Project, largest US Department of Energy laboratory. Budget $1.4 billion, Summit ~1.9 Eflop!
Neuromorphic wall

1024 TN chips, or 1 B neurons and 256 B synapses. Complexity of horse brain, 1/4 gorilla, 1/6 chimpanse.
Human Enhancement Perspectives
BCI: wire your brain ...

Non-invasive, partially invasive and invasive signals carry progressively more information, but are also harder to implement. EEG is still the king!
Brain-Computer-Brain Interfaces

Closed loop system with brain reading and stimulation for self-regulation. Sensory signals may come from Virtual Reality.
ECT – Electroconvulsive Therapy
VNS – Vagus Nerve Stimulation
Ultrasound, laser ... stimulation.
Complex techniques, but portable phones are also complex.
Attention? Just activate your cortex, no effort is needed!
HD EEG/DCS?

EEG electrodes + DCS.
Reading brain states
=> transforming to common space
=> duplicating in other brains

Applications:
depression, neuro-plasticity, pain, psychosomatic disorders, teaching!

Multielectrode DCS stimulation with 256 electrodes induces changes in the brain increasing neuroplasticity.
Your brain knows better what is interesting than you do! Information relevance (salience) from brain signals!


2. Violante et al. (2017) Externally induced frontoparietal synchronization modulates network dynamics and *enhances working memory* performance. *Elife 6, e22001*


Synchronize PFC/PC

DARPA (2016): **Neural Engineering System Design (NESD)**
Interface that reads impulses of $10^6$ neurons, injecting currents to $10^5$ neurons, and reading/activating $10^3$ neurons.

DARPA **Electrical Prescriptions (ElectRx)** project enables “artificial modulation of peripheral nerves to restore healthy patterns of signaling in these neural circuits. ElectRx devices and therapeutic systems under development are entering into clinical studies.”

Neural lace i neural dust project for cortex stimulation.
DARPA (2017): Enhance learning of a wide range of cognitive skills, with a goal of reducing the cost and duration of the Defense Department’s extensive training regimen, while improving outcomes. TNT could accelerate learning and reduce the time needed to train foreign language specialists, intelligence analysts, cryptographers, and others.
Memory implants


DARPA: Restoring Active Memory (RAM), new closed-loop, non-invasive systems that leverage the role of neural “replay” in the formation and recall of memory to help individuals better remember specific episodic events and learned skills.
Brain networks
Many processes go on in parallel, controlling homeostasis and behavior. Most are automatic, hidden from our Self. What goes on in my head?

Various subnetworks compete for access to the highest level of control - consciousness, the winner-takes-most mechanism leaves only the strongest. Signal Detection Theory: extract quasistable states/intentions from noise.
Though: time, position, energy, frequency

Spectrogram of words – distribution of energy in space/time/frequency – may be reconstructed from local field potentials measured using electrocorticography, and then used to activate voice synthesizer, changing brain activations to speech.
Patterns of cortical activations in higher order human auditory cortex allows for neural decoding of speech acoustic parameters, decoder is used to synthesize speech when a participant silently mimed sentences.

Global Neuronal Workspace Theory (Dehaene et al. 1998)

Brain is a substrate in which thoughts, feelings and intentions arise.
Neurocognitive Basis of Cognitive Control

Central role of fronto-parietal (FPN) flexible hubs in cognitive control and adaptive implementation of task demands (black lines=correlations significantly above network average). Cole et al. (2013).
Human connectome and MRI/fMRI

Structural connectivity

Functional connectivity

Graph theory

Whole-brain graph

Signal extraction

Correlation calculation

Node definition (parcelation)

Many toolboxes available for such analysis.

Bullmore & Sporns (2009)
fMRI analysis has many steps and variants of preprocessing.

Anatomical preprocessing pipeline.

fMRI analysis has many steps and variants of preprocessing.

Functional preprocessing pipeline.

Correlation matrix representing resting-state functional connectivity between selected brain regions Shows stronger connectivity for 7 large-scale brain networks: default mode (DM), dorsal attention (DAT), executive control network (FPN, CON), salience (SAL), sensorimotor (SOM), visual (VSN), auditory (ASN). Switching DMN ⇔ Salience ⇔ FPN
Sequence learning task: reproduce motion sequences represented on the screen as a visual stimuli. Automatization increases modularity, distinct subnetworks, reducing interference between different processes. 6-week motor sequence training resulted in autonomy of visual and motor areas.


Network neuroscience is focused on identifying network structures. Hubs, rich club and core of the network. Hubs connect modules via long-distance connections. Hubs are also often densely interconnected forming so called ’rich club’ or integrated core.

Development of brain in infancy: first learning how to move, sensorimotor activity organizes brain network processes, rather consistent.

The Developing Human Connectome Project: create a dynamic map of human brain connectivity from 20 to 44 weeks post-conceptional age, which will link together imaging, clinical, behavioral, and genetic information.

Pointing, gestures, pre-linguistic (our BabyLab).
ASD: pathological FC

Comparison of connections for patients with ASD (autism spectrum), TSC (Tuberous Sclerosis), and ASD+TSC.

**Coherence** between electrodes. Weak or missing connections between distant regions prevent ASD/TSC patients from solving more demanding cognitive tasks.

Network analysis becomes very useful for diagnosis of changes due to the disease and learning; **correct your networks**!

Biomarkers from neuroimaging

N. Yahata et al (2016): 29 selected regions (ROI) and 16 connections are sufficient to recognize ASD with 85% accuracy in 74 Japanese adult patients vs. 107 people in control group; without re-training accuracy was 75% on US patients.
Biomarkers of mental disorders

MDD, deep depression, SCZ, schizophrenia, OCD, obsessive-compulsive disorder, ASD autism spectrum disorder. fMRI biomarkers allow for objective diagnosis.

Intrinsic connectivity

Networks of functionally coupled regions.

Clustering results for 1000 young adults.

18,715 spatial locations are characterized by functional coupling to the 1,175 ROI vertices (FreeSurfer).

17-network intrinsic functional connectivity regions, from BTT Yeo et al. (2011). Colors = same network regions, similar correlation profiles.
Connectivity in patients vs healthy

Connectivity in patients vs healthy

Regions determined based on the 17-network solution from Yeo et al. Control (health) = circle, % deviation shown.
Negative connections in MCI patients

MCI patients (ADNI2), positive and negative functional connections in one of the 5 states of the Deep Auto-Encoder (DAE) + HMM models derived from the rs-fMRI time series.

Connections $|W| > 0.65$.

Accuracy 72.6% with a sensitivity of 70.6% and a specificity of 75%.

Suk et al. Neuroimage (2016)
MCI patients (ADNI2), positive and negative functional connections in one of the 5 states of the Deep Auto-Encoder (DAE) + HMM models derived from the rs-fMRI time series.

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Suk et al. Neuroimage (2016)
Decoding mental states

- Clear differences between fMRI brain activity when people read and think about different nouns.
- Reading words and seeing the drawing invokes similar brain activations, presumably reflecting semantics of concepts.
- Although individual variance is significant, similar activations are found in brains of different people, a classifier may still be trained on pooled data.
- Model trained on ~10 fMRI scans + very large corpus predicts brain activity for over 100 nouns for which fMRI has been done.

Sensory: fear, hear, listen, see, smell, taste, touch
Motor: eat, lift, manipulate, move, push, rub, run, say
Abstract: approach, break, clean, drive, enter, fill, near, open, ride, wear.

Are these 25 features defining brain-based semantics?
Quasi-stable brain activations?

Maintain brain activation for longer time. Use pictures, video, sounds ...

Can we induce stable cortical activation? Locate sources in similar areas as BOLD? Interpret brain activations in terms of brain-based semantics?

<table>
<thead>
<tr>
<th>Category</th>
<th>Exemplar 1</th>
<th>Exemplar 2</th>
<th>Exemplar 3</th>
<th>Exemplar 4</th>
<th>Exemplar 5</th>
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</thead>
<tbody>
<tr>
<td>animals</td>
<td>bear</td>
<td>cat</td>
<td>cow</td>
<td>dog</td>
<td>horse</td>
</tr>
<tr>
<td>body parts</td>
<td>arm</td>
<td>eye</td>
<td>foot</td>
<td>hand</td>
<td>leg</td>
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<tr>
<td>buildings</td>
<td>apartment</td>
<td>barn</td>
<td>church</td>
<td>house</td>
<td>igloo</td>
</tr>
</tbody>
</table>
Semantic neuronal space

Words in the semantic space are grouped by their similarity. Words activate specific ROIs, similar words create similar maps of brain activity. Video or audio stimuli, fMRI 60,000 voxel. Gallant lab, Berkeley.
Category zebra: Passive Viewing
Category zebra: Passive Viewing
Category traffic light: Passive Viewing
Each voxel responds usually to many related words, whole categories.

http://gallantlab.org/huth2016/

Huth et al. (2016). Decoding the Semantic Content of Natural Movies from Human Brain Activity. Frontiers in Systems Neuroscience 10, pp. 81
65 attributes related to neural processes; Colors on circle: general domains.

J.R. Binder et al
Toward a Brain-Based Componential Semantic Representation, 2016

More than just visual objects!
Decompose brain signals for a given concept into components coding these attributes.
Mental images from brain activity

Can we convert activity of the brain into the mental images that we are conscious of?

Try to estimate features at different layers.

8-layer convolution network, ~60 mln parameters, feature vectors from randomly selected 1000 units in each layer to simplify calculations.

Output: 1000 images.
fMRI activity can be correlated with deep CNN network features; using these features closest image from large database is selected. Horikawa, Kamitani, Generic decoding of seen and imagined objects using hierarchical visual features. Nature Comm. 2017.
Neurodynamics

Correlations of 6 canonical networks, 80 node parcellation

Each has up to 10 different network connectivity states (NC-states), rather stable for single subjects, ex. DMN has usually 7-9. NC identified from clusterization of patterns in 44.64 s tapered sliding window moved by 0.72 s over 14.4-minute scan.
DMN time-averaged baseline. Between-network allegiances (prob. that nodes are in the same community). Rim colors = canonical networks, rim length = greater allegiance to other networks, size of connections = strength of between-network allegiances. DMN1: weak within-network allegiance strong to DAT, SAL, and VIS.
EEG

Removal of artefacts is only partially automatic, it involves a lot of manual work. Usually only a subset of electrodes is selected.
Functional connectivity changes

Influence of brain games on functional connectivity: **Phase Locking Value** (Burgess, 2013; Lachaux 1999), phase differences between signals measured at each electrode. PLV => synchronization maps, info flow.

\[ PLV(a, b) = \frac{1}{T} \sum_{t} e^{i\Phi(t)} \]

**PLV channel vs channel**
Microstates

Lehmann et al. EEG microstate duration and syntax in acute, medication-naïve, first-episode schizophrenia. Psychiatry Research Neuroimaging, 2005

Khanna et al. Microstates in Resting-State EEG. Neuroscience and Biobehavioral Reviews, 2015

4-7 states 60-150 ms Symbolic dynamics.
EEG localization and reconstruction

Checkerboard reversal, 5 microstates

M1 => V1
M2 => V2
M3 => Para-hippocampal
M4 => BA7, left PC, precuneus
M5 => dACC

A. Keitel i J. Gross, „Individual human brain areas can be identified from their characteristic spectral activation fingerprints”, *PLoS Biol* 14(6), e1002498, 2016
8 large networks from BOLD-EEG

DMN, FP (frontoparietal)-left, right, sensorimotor, ex, control, auditory, visual (medial), (H) visual (lateral). Yuan ... Bodurka (2015)
14 networks from BOLD-EEG

sICA on 10-min fMRI data ($N = 24$, threshold: $p < 0.01$, TFCE corrected). DMN, default mode network; DAN, dorsal attention network; DSN, dorsal somatomotor network; VFN, visual foveal network; AN, auditory network; MPN, medial prefrontal network.
<table>
<thead>
<tr>
<th>Region</th>
<th>EEG-RSN Maps Obtained Using Spatial ICA</th>
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<tbody>
<tr>
<td>DMN</td>
<td>![DMN EEG-RSN Map]</td>
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<td>DAN</td>
<td>![DAN EEG-RSN Map]</td>
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<td>VAN</td>
<td>![VAN EEG-RSN Map]</td>
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<td>rFPN</td>
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<td>IFPN</td>
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<td>LN</td>
<td>![LN EEG-RSN Map]</td>
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<td>CON</td>
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<td>AN</td>
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<tr>
<td>VSN</td>
<td>![VSN EEG-RSN Map]</td>
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<td>DSN</td>
<td>![DSN EEG-RSN Map]</td>
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<td>VFN</td>
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<tr>
<td>VPN</td>
<td>![VPN EEG-RSN Map]</td>
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<tr>
<td>MPN</td>
<td>![MPN EEG-RSN Map]</td>
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<tr>
<td>LPN</td>
<td>![LPN EEG-RSN Map]</td>
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</tbody>
</table>

*Note: Each EEG-RSN map corresponds to a different functional network, represented by t-scores ranging from min to max.*
Final words
Possible form of Brain Fingerprints

fMRI: BFP is based on $V(X,t)$ voxel intensity of fMRI BOLD signal changes, contrasted between task and reference activity or resting state.

EEG: spatial, spatio-temporal, ERP maps/shapes, coherence, various phase synchronization indices.

1. **Spatial/Power**: direct localization/reconstruction of sources.
2. **EEG microstates**, sequences & transitions, dynamics in ROI space.
3. **Spatial/Synch**: changes in functional graph network structure.
4. **Frequency/Power**: ERS/ERD smoothed patterns $E(X,t,f)$.
5. **ERP global power maps**: spatio-temporal averaged energy distributions.
6. **EEG decomposition into components**: ICA, CCA, tensor, RP ...
7. Model-based: **The Virtual Brain**, integrating EEG/neuroimaging data.
8. Spectral fingerprinting (MEG, EEG), power distributions.

Neuroplastic changes of connectomes and functional connections as results of training for optimization of brain processes.
Conclusions

• Hierarchically modularized set of canonical networks is the best description of the brain. Connectomes form static localized networks, enabling dynamic, whole-brain states. We can use fMRI techniques to determine static structures that change slowly due to the neuroplasticity.

• Temporal state dynamics is based on rapid resynchronization of subnetworks on connectome scaffolding. Time scale of the order of 10 ms requires EEG/MEG or NiRS techniques. Activity of deeper brain structures is difficult to measure reliably. Invasive techniques have limited applicability in case of humans, but this may change if DARPA projects will be successful.

• Neurodynamics is the key to understanding of mental states, but it requires models of information processing that will help to interpret network states and their transitions. Influence of other RDoC levels on mental states may be understood indirectly, via changes in neurodynamics.

• Neuroimaging, M/EEG, etc. ↔ models of whole brain (TVB) ↔ networks, neurodynamics ↔ interpretation, mental states: S(B) ↔ S(M).
Perspectives

• Many brain states are now linked to specific mental states, and can be transformed into signals that we can understand: motor intentions, plans, images, inner voices ...

• Some large-scale functional networks have reasonable (although still not perfect) interpretation, for example sensory networks, dorsal and ventral attention networks, executive control, motor networks.

• Individual differences and many psychological functions are directly linked to connectome and functional networks, including multistable properties.

• AI/ML draws inspirations from brain research, but also neural network models and learning algorithms (CNN, recurrence networks, reinforcement learning) help to interpret information processing in the brain.

• Many neurocognitive technologies are coming, helping to diagnose, repair and optimize brain processes.
In search of the sources of brain's cognitive activity

Project „Symfonia”, 2016-21
My group of neuro-cog-fanatics
Soul or brain: what makes us human?
Interdisciplinary Workshop with theologians,

Monthly international developmental seminars (2017): Infants, learning, and cognitive development

Disorders of consciousness
17-21.09.2017

Autism: science, therapies
23.05.2017
International Neuroinformatics Coordination Facility (INCF) goal: integrate and analyze diverse data across scales, techniques, and species to understand the brain and positively impact the health and well-being of society.

Polish INCF Node, established in Warsaw at the Nencki Institute, since 2017 at the Nicolaus Copernicus University in Toruń.


Speakers

Jan Bjaalie, University of Oslo
Rafal Bogacz, University of Oxford
Andrzej Cichocki, RIKEN CBS
Maureen Clerc, Inria
Carole Goble, University of Manchester
William Grisham, UCLA
Michael Hawrylycz, Allen Institute for Brain Science
Henry Kennedy, NSERM
Naomi Penfold, ASAPbio
Ariel Rokem, University of Washington
Frances Skinner, University of Toronto
Pedro Valdes-Sosa, Cuban Neuroscience Center, University of Electronic Science and Technology China
Kirstie Whitaker, University of Cambridge
Alexander Woodward, RIKEN CBS

Session 9

- Global infrastructure interoperability
- Data management and workflows
- Future of computing
- Comparative and pred

Thank you for synchronization of your neurons

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