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NEUROSURGERY GRAND ROUNDS  --  2/24/2017

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Your cellphone number will never be used for anything but the recording of your attendance; you only get a text back if you text us first.

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A NETWORK NEUROSCIENCE OF HUMAN LEARNING:
POTENTIAL TO INFORM QUANTITATIVE THEORIES OF BRAIN AND BEHAVIOR

JEFFERSON
PHILADELPHIA, PA
FEBRUARY 24, 2017

Danielle S. Bassett

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Neural Signatures of Learning

Synaptic changes
Shepherd lab

White or gray matter changes
Scholz et al. 2009

White matter architecture
Kahn et al. 2009
Functional signatures of learning

Activity changes

Functional or effective connectivity changes

Dayan & Cohen, 2011

MoNET Lab
Scaling beyond 2-3 connections

Cognitive processes (including learning) often require varied computations performed by many different regions, and they also often elicit activity in spatially distributed circuits.

A network focus on learning

Structural network substrates supporting learning
• Kahn et al. 2016 Cerebral Cortex

Structural network substrates supporting other cognitive processes necessary for learning

Functional network substrates supporting learning
A network focus on learning

Structural network substrates supporting learning
- Kahn et al. 2016 Cerebral Cortex

Structural network substrates supporting other cognitive processes necessary for learning

Functional network substrates supporting learning
Substrates for adaptation & learning

- Modularity of structure & morphology
- Modularity of mind
- Modularity of networks
Are functional brain networks modular?

Does modularity help us to understand large-scale neural signatures of adaptation and learning?
Functional brain networks:
Co-activation, coupling, communication

**Network nodes:** large-scale regions defined by anatomical boundaries.

**Network edges:** Coherence between wavelet coefficients; decomposition extracting 0.06-0.12 Hz information from BOLD time series collected during task performance.

\[
\text{Coh}(f) = \frac{|S_{yx}(f)|^2}{S_{xx}(f)S_{yy}(f)}
\]

- Cross-spectral density between x and y
- Autospectral density of x or y
Modularity in functional brain networks

In a single time window, the network of interactions between brain regions displays community structure.

$$Q_s = \frac{1}{2\bar{w}} \sum_i \sum_j \left( \bar{w}_{ij} - \frac{\bar{w}_i \bar{w}_j}{2\bar{w}} \right) \delta(C_i, C_j)$$

Modularity maximization.

Chen et al. Cereb Cortex 2008

Nelson et al. Neuron 2010
How do functional brain networks support *dynamic* cognitive processes like adaptation and learning?
Dynamic Networks in the Brain

How do brain communication patterns change over time?

Bassett et al. PNAS 2011
Dealing with Temporal Networks

- Turns an adjacency matrix into an adjacency tensor.
- Allows us to inform solutions in one layer with solutions in neighboring layers.

Bassett et al. 2013 Chaos
Community Structure in Multilayer Networks


$$Q = \frac{1}{2\mu} \sum_{i,j,l,r} \left\{ (A_{ijl} - \gamma_l P_{ijl}) \delta_{l,r} + \delta_{i,j} \omega_{j,l,r} \right\} \delta(g_{il}, g_{jr}),$$

Bassett et al. 2013 Chaos

Mucha et al. 2010 Science
Flexibly Reconfiguring Modules

**Flexibility:** fraction of times that nodes change modules.

**Promiscuity:** number of modules nodes change among.

**Cohesiveness:** measures the degree to which nodes change in concert with one another, moving as a group *versus* as independent units.

Bassett et al. 2011 PNAS; Papadopoulous et al. 2016 Phys Rev E; Telesford et al. 2016 In Revision
Network dynamics supporting learning, memory, and cognitive flexibility

Flexibility in network modules is often observed in fronto-parietal cognitive control areas and predicts individual differences in:

- Visuo-motor learning (Bassett et al. 2011 PNAS; Bassett et al. 2015 Nature Neuroscience)
- Cognitive flexibility (Braun et al. 2015 PNAS)
- Working memory (Braun et al. 2015 PNAS)
- Reinforcement learning rate (Gerraty … Shohamy, 2016, Submitted)
During visuo-motor learning

6 weeks of training

training sessions:
#1-10  #11-20  #21-30
14 days  14 days  14 days

SCAN 1.5 hr  SCAN 1.5 hr  SCAN 1.5 hr  SCAN 1.5 hr
Flexible Growth in Autonomy

Motor-visual co-assignment decreases with training.

Training-dependent modulation
  ➢ autonomy

Bassett et al. 2015 Nat Neuro
Flexible disconnection of cognitive control

- The rest of the brain becomes less and less connected.

This fronto-cingulate network houses critical hubs of cognitive control.

To what degree is flexibility a state or a trait?

Can we intervene with lifestyle changes or drugs to alter flexibility?

Would such interventions enhance learning?
A Positive Mood, a Flexible Brain

Betzel et al. 2016, In Revision at Sci. Reports

Brain Flexibility

Positivity

Attentive

Rested and Fed

Global flexibility

PC4, Surprise Index (SI)

$\ r = 0.407$

$p = 3.4 \times 10^{-4}$
We can give people medicine to increase brain flexibility.

41 Controls undergoing pharmacological challenge with an N-Methyl-D-Aspartate (NMDA) receptor antagonist: Dextromethorphan.

Braun et al. 2016, PNAS
Is Flexibility Always Good?

Healthy, High Functioning Adult
Bassett et al. 2011 PNAS;
Braun et al. 2015 PNAS;
Bassett et al. 2015 Nat Neurosci

Children
Chai et al. 2016
Network Neuroscience

Schizophrenia
Siebenhuhner et al. 2013
PLoS One;
Braun et al. 2016 PNAS
Interim summary

Visuo-motor learning
Cognitive flexibility
Working memory
Reinforcement learning rate

Digging in deeper:
1. **Neuro**: Understanding the role of different neurotransmitters
2. **Real-world**: Studying classroom learning
3. **Math**: Using more sophisticated methods
3. **Math**: Using more sophisticated methods

What are specific deficiencies of the current methods?
Dynamic functional networks

Temporal space of brain graphs is composed of subgraphs
Dynamic functional networks

Temporal space of brain graphs is composed of subgraphs

Measured Connectivity

Subgraphs

Patterns of recurring connections
(co-varying edge weights)
Clustering dynamic functional connectivity

Pairwise Connections

Time Windows

Subgraph Learning

Non-negative matrix factorization

\[ \hat{A} \approx WH \]

Connectivity matrix 
\( (C \times T) \)

Subgraph matrix 
\( (C \times k) \)

Expression coefficients 
\( (k \times T) \)

Chai et al. 2016 Network Neuroscience
Khambhati et al. 2017 Eneuro, In Press
Subgraphs reveal topological modes
System-level interactions during resting state

Chai et al. (2016) *In Press: Network Neuroscience*
Evolution of Brain Network Dynamics in Neurodevelopment

Results

A fronto-parietal subgraph showed highest energy and entropy over youth ages 8 to 22.

Its expression was greater in older youth, as was its transience in expression.

Greater transience was associated with greater overall task accuracy on a cognitive battery (n=780).

Chai et al. 2016 Network Neuroscience
Khambhati et al. 2017 Eneuro, In Press
What does NMF buy us in studying learning?

Kambhati, Mattar, Bassett (2017)
http://biorxiv.org/content/early/2017/01/02/097691
What are those non-module subgraphs?

Are modules not the canonical forms supporting adaptation and learning?

If not, what are the canonical forms?
Are modules the canonical form of brain structure and function?

- Modular
- Bipartite
- Core-Periphery
- All of the above

Betzel et al. 2017
arXiv:1702.02807
Weighted stochastic block models

Assortative

Disassortative

Core-periphery

Mixed

Connection weight

Weaker

Stronger

I
II
III
IV

I-II
III-IV
I-III

Danielle S. Bassett

Betzel et al. 2017
arXiv:1702.02807
3. Math: Using more sophisticated methods
   1. Non-negative matrix factorization
   2. Weighted stochastic block models
Where to next … bridging to models of behavior
Behavior: Existing models … New models

Reinforcement learning models of behavior

Gerraty … Shohamy, 2016, Submitted

Multivariate graphical models of behavior

Wymbs et al., 2012, Neuron
Summary

Visuo-motor learning
Cognitive flexibility
Working memory
Reinforcement learning rate

1. **Math:**
   1. NMF
   2. WSBMs

2. **Behavior:**
   1. Reinforcement learning models
   2. Multivariate graphical models
A Network Neuroscience of Human Learning: Potential to Inform Quantitative Theories of Brain and Behavior

Bassett & Mattar, TICS, In Press.
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Questions?
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Your attendance has been recorded for "Talk 1: FLAIR signal and volumetric analysis for materializing temporal lobe epilepsy. Talk 2: Rates of screening ultrasound before and after enactment of the PA Breast Density Notification Act."

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What is happening in the brain during learning?

Session 1

Session 2

Session 3

75 networks

Bassett et al. 2011 PNAS
Motor Skill Learning (a.k.a. Guitar Hero)

Bassett et al. 2011 PNAS
Mantzaris et al. 2013 J Compl Nets

Experimental Paradigm:
Sequential Movement Task Over 3 Days

Estimate Learning:
Exponential drop-off parameter of movement time versus trial bin

What is happening in the brain during learning?
Flexibility Predicts Adaptive Function

People with higher flexibility on one day will learn better on the following day than people with lower flexibility.

Regional flexibility is critical in association cortex rather than primary sensorimotor cortex.

Bassett et al. 2011 PNAS
Mechanics of NMF

\[ \min_{W,H} \frac{1}{2} \{ \| A - WH \|_F^2 + \eta \| W \|_F^2 + \beta \sum_{j=1}^{n} \| H(:,j) \|_1^2 \}, \ s.t. W, H \geq 0 \]

- Non-deterministic algorithm (integrate over multiple runs)
- Alternating non-negative least squares regression (\( W \rightarrow H, H \rightarrow W \))
- Parameter optimization: \( k, \eta, \beta \)
- \( W \) and \( H \) form a set of basis set of subgraphs and weights

Lee and Seung (1999)
*Nature*
Kim and Park (2007)