NETWORK ANALYSIS OF NEUROFEEDBACK DATA FROM SCHIZOPHRENIFORM BRAINS

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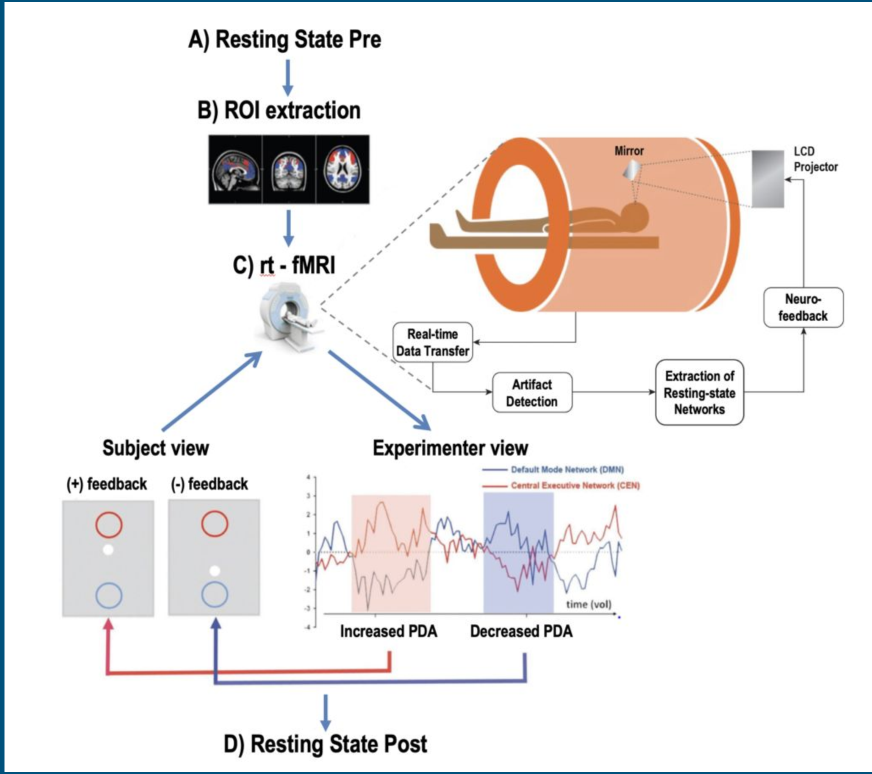
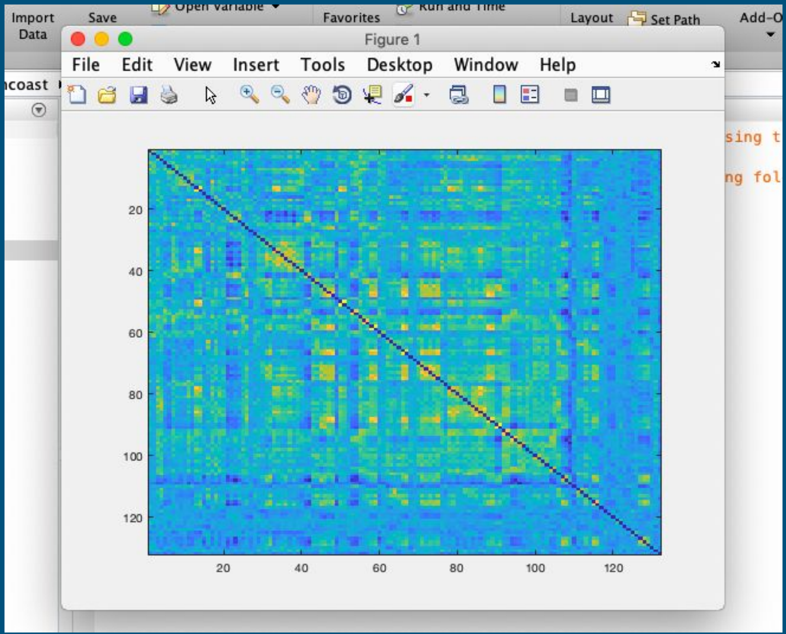
What are we doing?: A refresher

- Our data comes from schizophrenic subjects playing a game involving mindfulness meditation
- fMRI run during the game measures connectivity of brain areas:
  - Default Mode Network
  - Central Executive Network
- In a network sense, our data is the correlations of brain regions in an atlas — edges weighted in [-1, 1]
  - 120 readings — 15 subjects, 8 trials
  - Fully connected networks of N = 132



Source Data

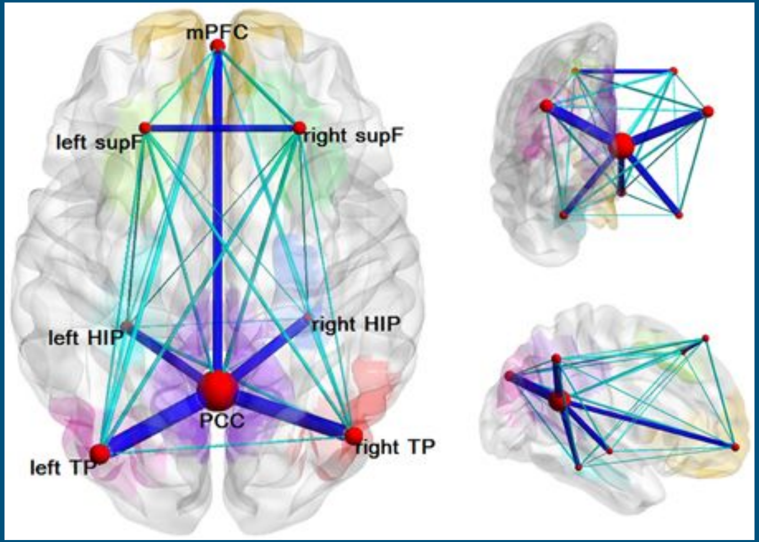


Correlation matrix between atlas regions

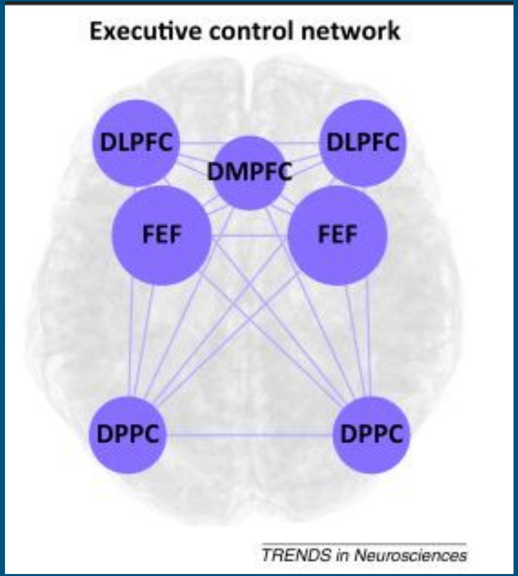
```
aMTG r (Middle Temporal Gyrus, anterior division
aMTG l (Middle Temporal Gyrus, anterior division
pMTG r (Middle Temporal Gyrus, posterior divisior
pMTG l (Middle Temporal Gyrus, posterior divisior
toMTG r (Middle Temporal Gyrus, temporooccipital
toMTG l (Middle Temporal Gyrus, temporooccipital
aITG r (Inferior Temporal Gyrus, anterior divisic
aITG l (Inferior Temporal Gyrus, anterior divisic
pITG r (Inferior Temporal Gyrus, posterior divisi
pITG l (Inferior Temporal Gyrus, posterior divisi
toITG r (Inferior Temporal Gyrus, temporooccipita
toITG l (Inferior Temporal Gyrus, temporooccipita
PostCG r (Postcentral Gyrus Right)
PostCG l (Postcentral Gyrus Left)
SPL r (Superior Parietal Lobule Right)
SPL l (Superior Parietal Lobule Left)
aSMG r (Supramarginal Gyrus, anterior division Ri
aSMG l (Supramarginal Gyrus, anterior division Le
pSMG r (Supramarginal Gyrus, posterior division F
pSMG l (Supramarginal Gyrus, posterior division L
AG r (Angular Gyrus Right)
AG l (Angular Gyrus Left)
sLOC r (Lateral Occipital Cortex, superior divisi
sLOC l (Lateral Occipital Cortex, superior divisi
iLOC r (Lateral Occipital Cortex, inferior divisi
iLOC l (Lateral Occipital Cortex, inferior divisi
ICC r (Intracalcarine Cortex Right)
ICC l (Intracalcarine Cortex Left)
MedFC (Frontal Medial Cortex)
SMA r (Juxtapositional Lobule Cortex -formerly Su
SMA L(Juxtapositional Lobule Cortex -formerly Sup
SubCalC (Subcallosal Cortex)
PaCiG r (Paracingulate Gyrus Right)
PaCiG l (Paracingulate Gyrus Left)
AC (Cingulate Gyrus, anterior division)
PC (Cingulate Gyrus, posterior division)
Precuneous (Precuneous Cortex)
Cuneal r (Cuneal Cortex Right)
Cuneal l (Cuneal Cortex Left)
```

The Harvard-Oxford Brain Atlas

Network Viz



Sample Structural Network of the DMN (Adapted from [1])



Schematic anatomical overview of salience and executive control networks. (Adapted from [2])

(Our DMN/CEN node maps were taken from [3])

Our DMN and CEN

DMN Regions:

- Posterior cingulate/precuneus
  - 55: 'PC (Cingulate Gyrus, posterior division)', -
  - 56: 'Precuneous (Precuneous Cortex)',
- Medial Prefrontal
  - 48: 'MedFC (Frontal Medial Cortex)',
- Left lat parietal
  - 80: 'PO l (Parietal Operculum Cortex Left)',
- Right lat parietal
  - 79: 'PO r (Parietal Operculum Cortex Right)',
- Left inf temp
  - 27: 'aITG l (Inferior Temporal Gyrus, anterior division Left)',
  - 29: 'pITG l (Inferior Temporal Gyrus, posterior division Left)',
  - 31: 'toITG l (Inferior Temporal Gyrus, temporooccipital part Left)',
- Right inf temp
  - 26: 'aITG r (Inferior Temporal Gyrus, anterior division Right)',
  - 28: 'pITG r (Inferior Temporal Gyrus, posterior division Right)',
  - 30: 'toITG r (Inferior Temporal Gyrus, temporooccipital part Right)',
- Med dors thal
  - 91: 'Thalamus r',
  - 92: 'Thalamus l',
- Right posterior cerebellum
  - 115: 'Cereb6 r (Cerebelum 6 Right)',
  - 117: 'Cereb7 r (Cerebelum 7b Right)',
  - 119: 'Cereb8 r (Cerebelum 8 Right)',
  - 121: 'Cereb9 r (Cerebelum 9 Right)',
- Left posterior cerebellum
  - 114: 'Cereb6 l (Cerebelum 6 Left)',
  - 116: 'Cereb7 l (Cerebelum 7b Left)',
  - 118: 'Cereb8 l (Cerebelum 8 Left)',
  - 120: 'Cereb9 l (Cerebelum 9 Left)',

CEN regions:

- Dorsal medial PFC
  - 4: 'SFG r (Superior Frontal Gyrus Right)',
  - 5: 'SFG l (Superior Frontal Gyrus Left)',
  - 6: 'MidFG r (Middle Frontal Gyrus Right)',
  - 7: 'MidFG l (Middle Frontal Gyrus Left)',
- Left ant PFC
  - 1: 'FP l (Frontal Pole Left)',
- Right ant PFC
  - 0: 'FP r (Frontal Pole Right)',
- Left superior parietal
  - 35: 'SPL l (Superior Parietal Lobule Left)',
- Right superior parietal
  - 34: 'SPL r (Superior Parietal Lobule Right)',

Regions taken from [3], adapted to fit Harvard-Oxford atlas

CEN and DMN: a general idea

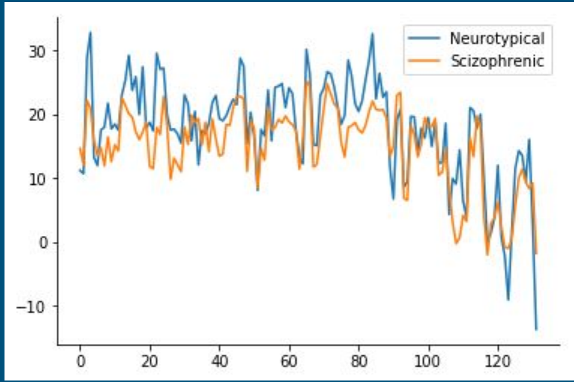
- it is now known that [the DMN] can contribute to elements of experience that are related to external task performance It is also active when the individual is thinking about others, thinking about themselves, remembering the past, and planning for the future. [4]
- CEN: “selecting and successfully monitoring behaviors that facilitate the attainment of chosen goals.” [5]
- The study that we attained this data from was using meditative practices to activate the CEN and deactivate the DMN in patients

Methods

- Our main workflow for network statistics was schizophrenic (SZ) and neurotypical (NT) graph comparison
  - Results averaged across individual graphs for a wholesale NT vs SZ comparison
- For some network statistics we were able to work in the weighted space
  - For some, we used a minimum spanning tree method to generate a non-complete binary graph
  - Started with the minimum spanning tree, then built up to a desired density

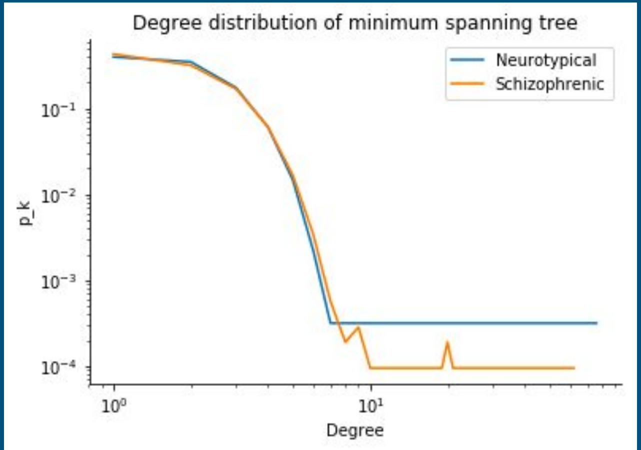
```python
# strength : Graph -> Dict(Node, Strength)
# Plots the strength dict of a given graph. Strength values can be negative.
# *args:
# - default: no condition on which edges are considered
# - pos_only: only positive edges are considered
# - neg_only: only negative edges are considered
# - range: values between the next two inputted numbers will be considered
def strength(G, *args):

    if len(args) == 0:
        cond = lambda x: True
    elif args[0] == 'pos_only':
        cond = lambda x: x > 0
    elif args[0] == 'neg_only':
        cond = lambda x: x < 0
    elif args[0] == 'range':
        cond = lambda x: x > args[1] and x < args[2]

    G_strength = {}
    for node in G.nodes():
        node_strength = 0
        for neighbor in G.neighbors(node):
            neighbor_strength = G[node][neighbor]['weight']
            if math.isnan(neighbor_strength):
                continue
            elif cond(neighbor_strength):
                node_strength += neighbor_strength

        G_strength[node] = node_strength

    return G_strength
```

Code: find strength dist. of weighted graph

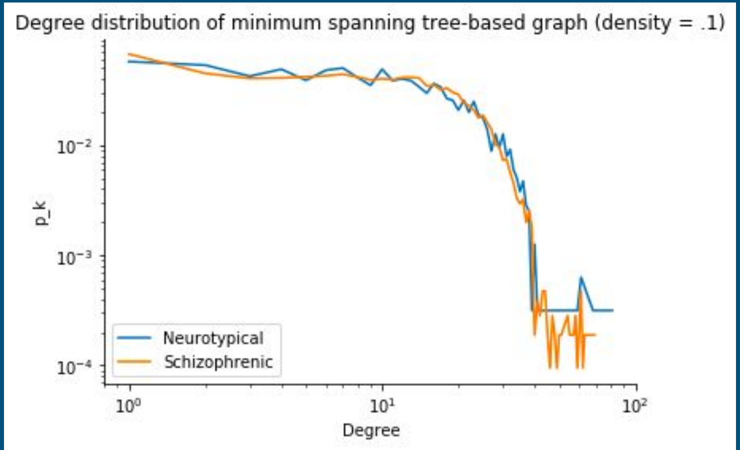


Averaged strength dists. of SZ and NT graphs

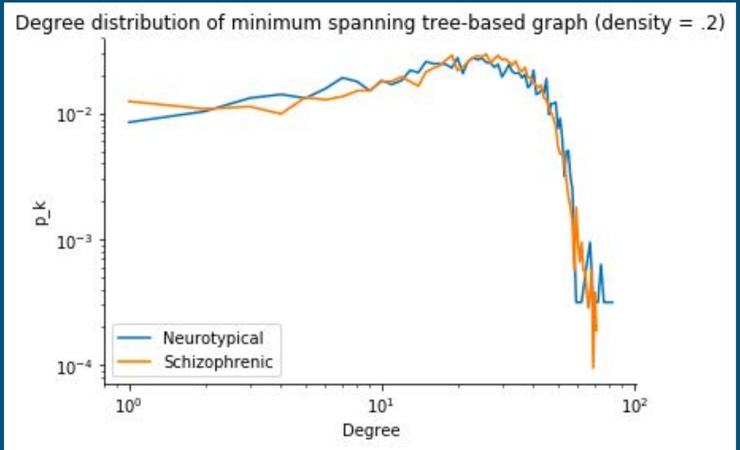
Degree



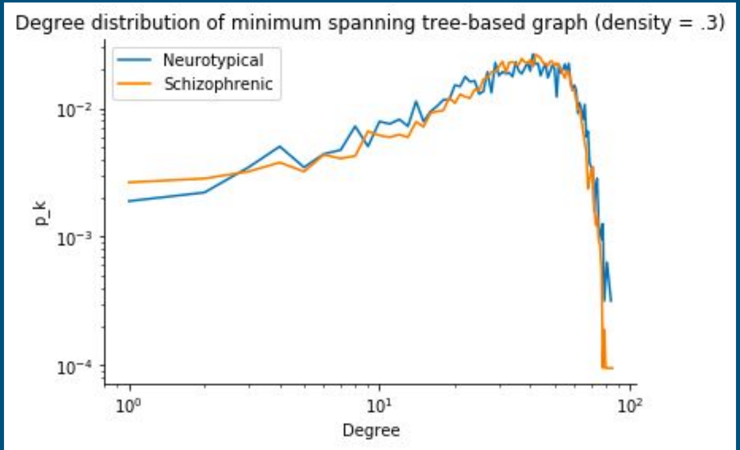
Degree distribution of minimum spanning tree
Neurotypical
Schizophrenic
p_k
Degree



Degree distribution of minimum spanning tree-based graph (density = .1)
Neurotypical
Schizophrenic
p_k
Degree

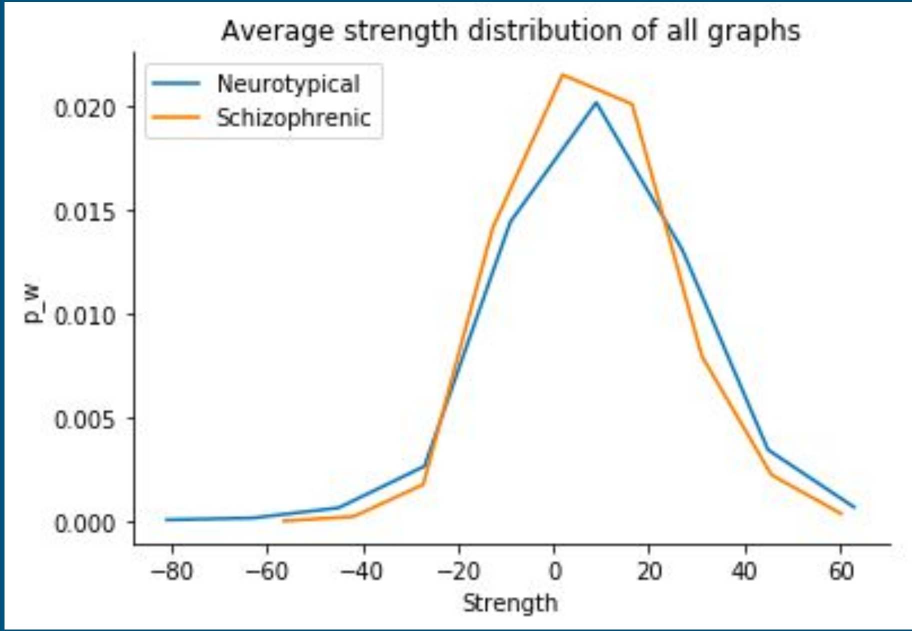


Degree distribution of minimum spanning tree-based graph (density = .2)
Neurotypical
Schizophrenic
p_k
Degree



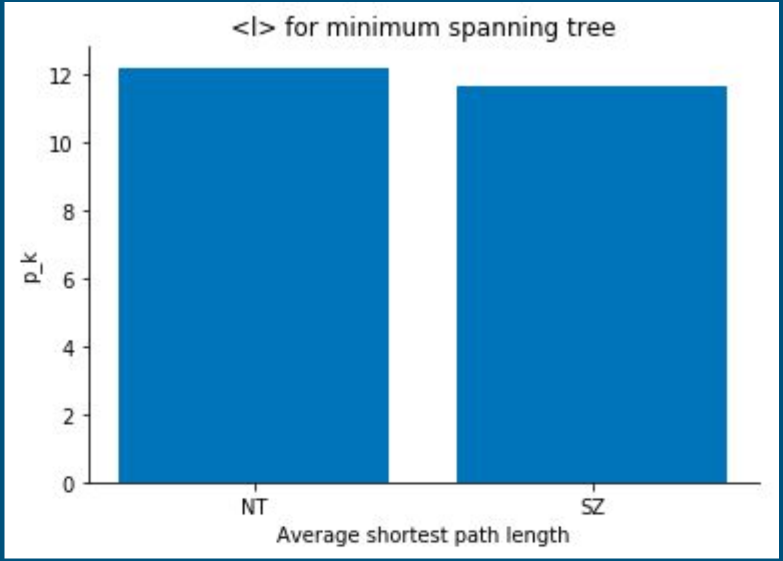
Degree distribution of minimum spanning tree-based graph (density = .3)
Neurotypical
Schizophrenic
p_k
Degree

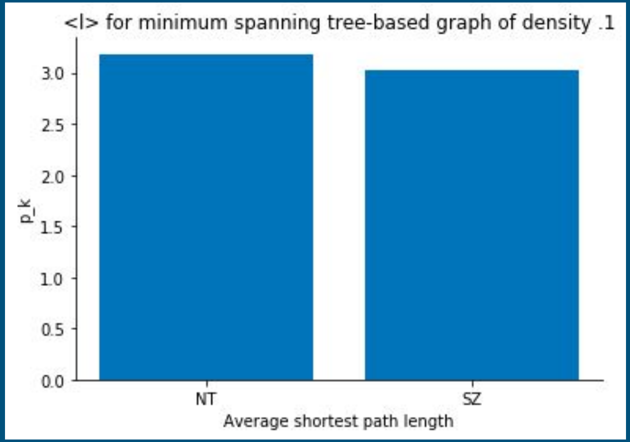
Strength

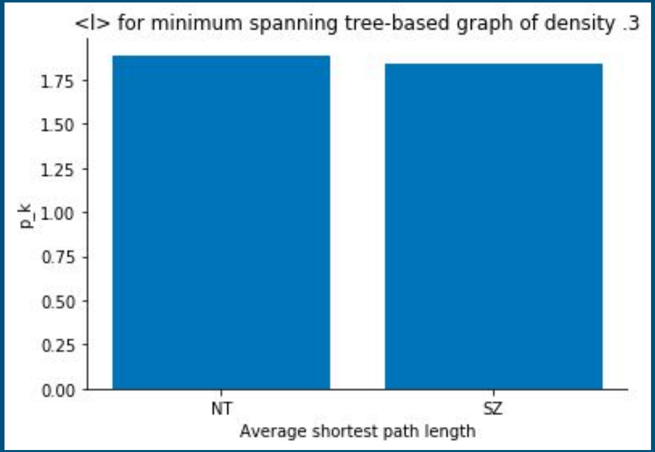


Average strength distribution of all graphs
Neurotypical
Schizophrenic
p_w
0.020
0.015
0.010
0.005
0.000
−80
−60
−40
−20
0
20
40
60
Strength

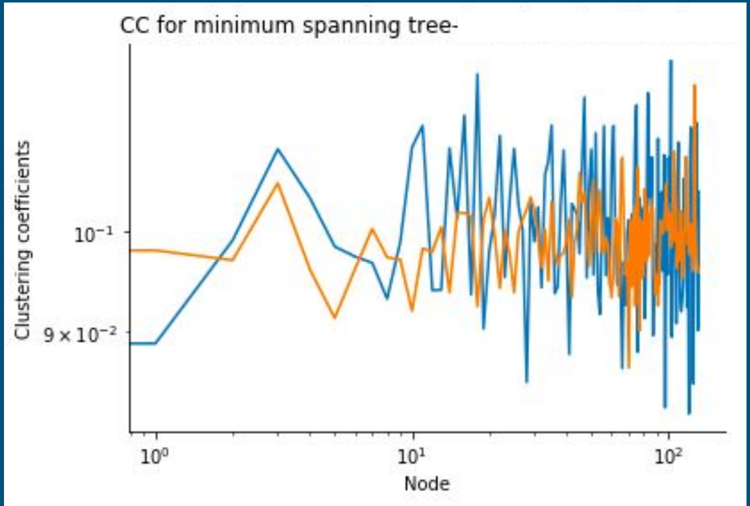
Average Path Length

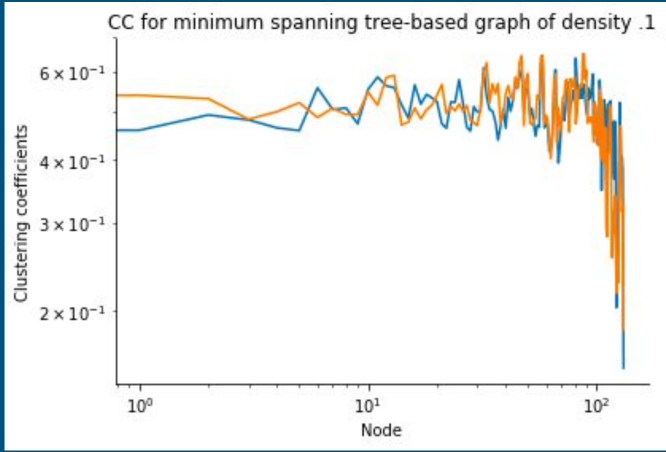


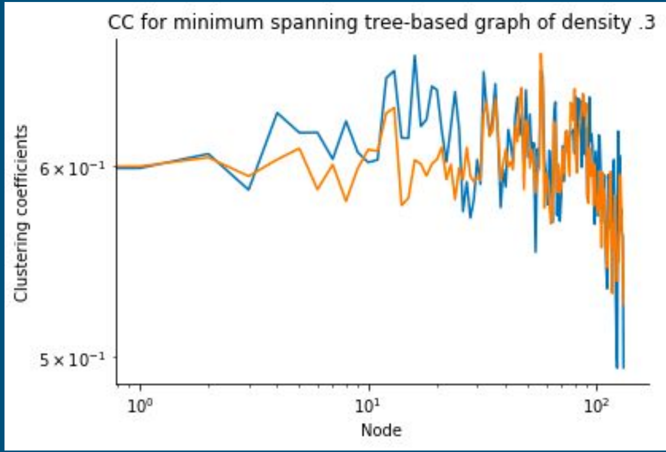




Clustering Coefficient

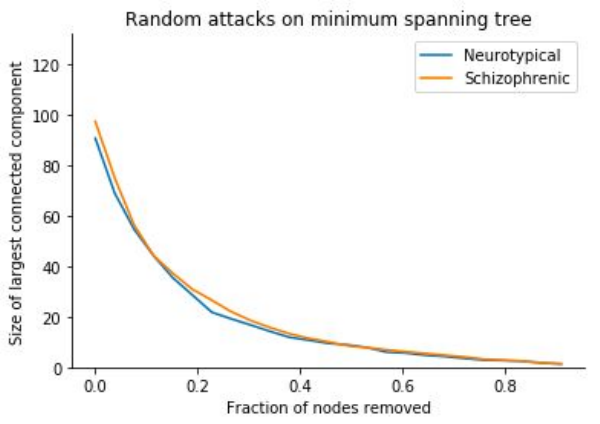


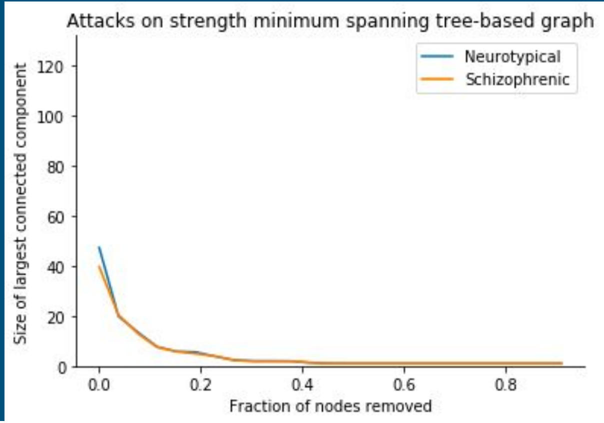




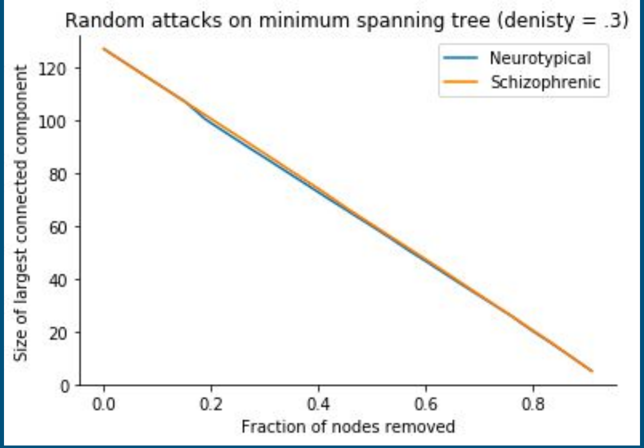
Network Robustness

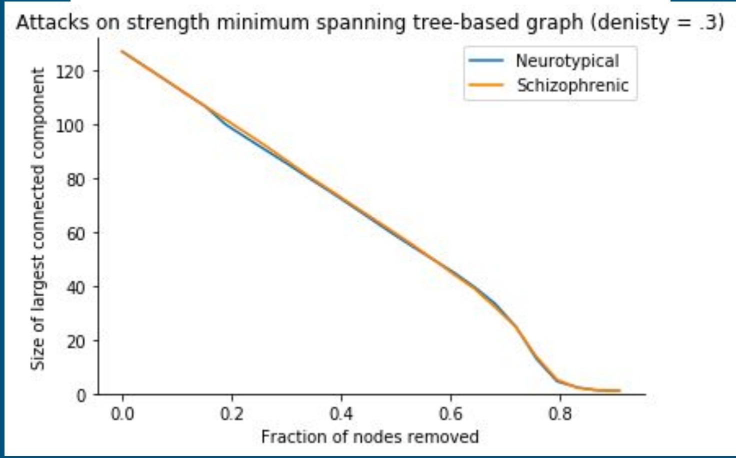
Minimum spanning tree





MST-based graphs with density of .3

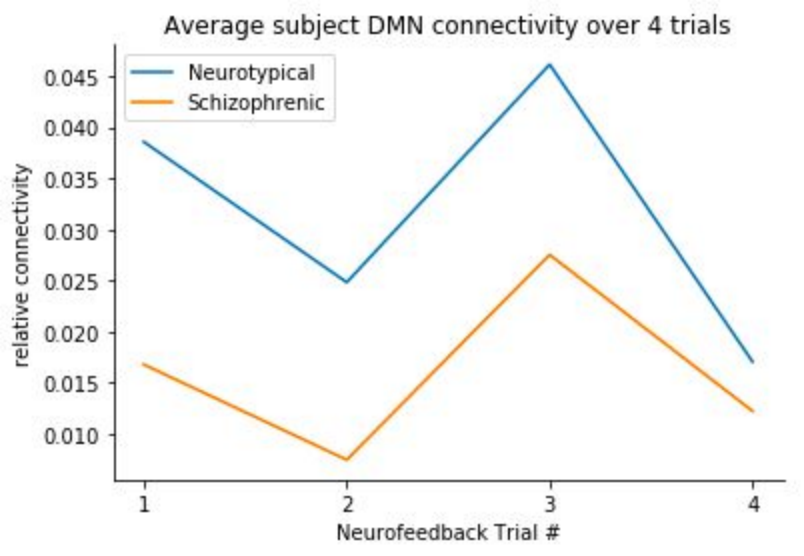




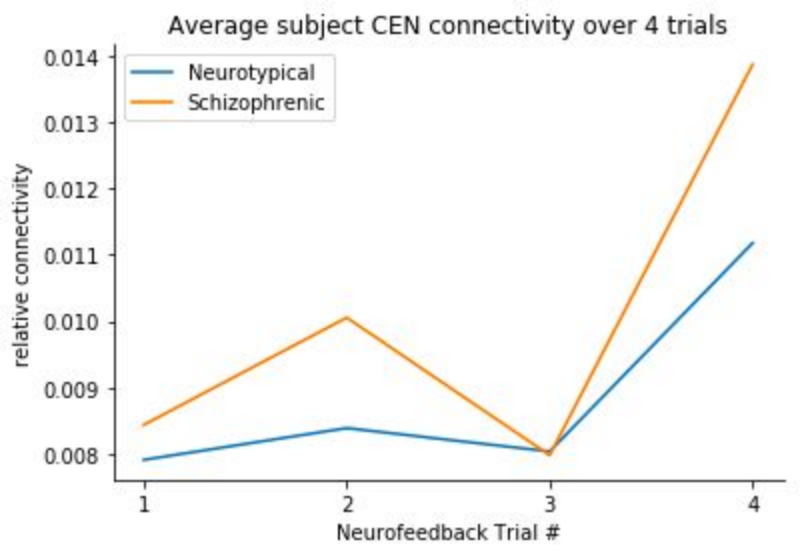
Random Attacks

Degree-based attacks

DMN/CEN Connectivity



DMN connectivity over trials



CEN connectivity over trials

(DMN/CEN node maps were taken from [3])

Conclusions

- The weighted brain appears as a random network
- With repeated practice, subjects on average increased their CEN connectivity and decreased their DMN connectivity
  - This confirms conventional wisdom about mindfulness meditation

References

- [1] — Tao Y, Liu B, Zhang X, Li J, Qin W, Yu C and Jiang T (2015) The Structural Connectivity Pattern of the Default Mode Network and Its Association with Memory and Anxiety. *Front. Neuroanat*. 9:152. Doi: 10.3389/fnana.2015.00152
- [2] — Hermans et al., Dynamic adaptation of large-scale brain networks in response to acute stressors, Trends in neurosciences Volume 37, Issue 6, June 2014, Pages 304-314
- [3] — Marcus E. Raichle.Brain Connectivity.Jan 2011.ahead of print http://doi.org/10.1089/brain.2011.0019