Neural Correlates of Fluid Intelligence via Functional and Structural Network Connectivity Measures

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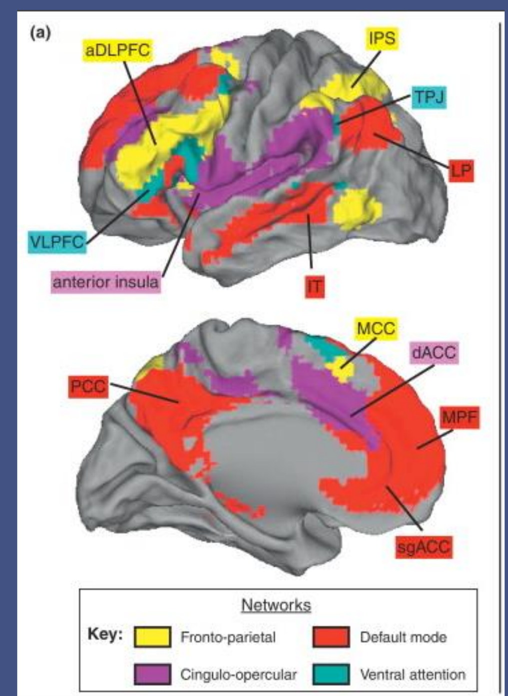
Introduction

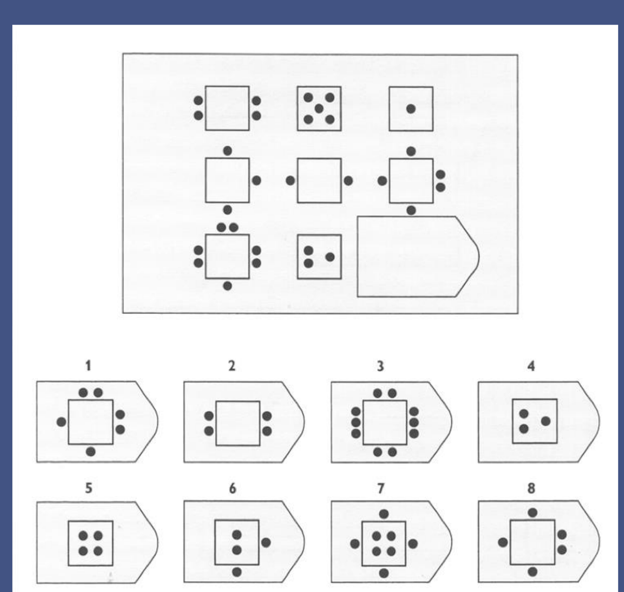
- Connectivity across regions in the brain can be characterized as either functional (FC; correlated fluctuations in brain activity as measured by fMRI data) or structural (SC; white matter pathways as measured by diffusion-weighted MRI data, dMRI).[1]
- Emerging studies suggest that the patterns of connectivity across brain regions that make up distinct cognitive networks can partially explain individual differences in behavioral traits.[2,4,5]
- One benchmark of fluid intelligence is the domain-invariant ability to identify and extrapolate patterns across distantly related ideas.[1,4,5]
- The Fronto-Parietal Network (FPN) and Cingulo-Opercular Network (CON) have been shown to be associated with aspects of higher-order cognitive functions.[6-8]
- The CON has been shown to down-regulate activity in the Default Mode Network (DMN) by acting as a cognitive "switchboard", preventing the DMN from engaging in self-referential thinking, and thus allowing one to concentrate on the task at hand.[7]



- Extending previous research[8], we hypothesized that the SC and FC between the FPN, CON, and DMN could be predictive of a person's fluid intelligence.
- In the present study, we trained a support vector regression model using data provided by the *Human Connectome Project* (HCP)[10*] to assess the degree to which the FC and SC within and across brain networks might account for variance in fluid intelligence scores.

Cognitive Task Paradigm

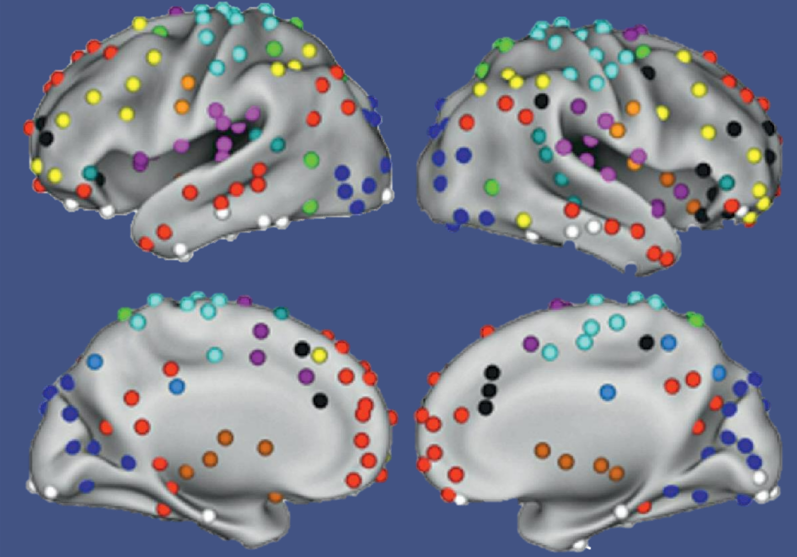
Raven's Progressive Matrices



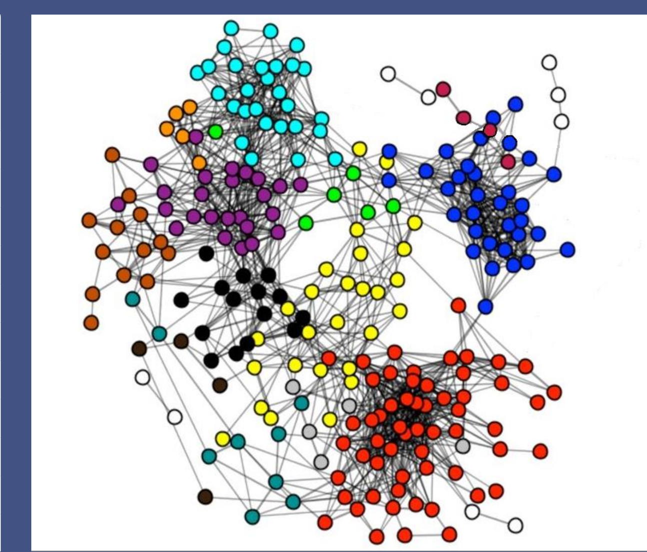
- Fluid Intelligence was assessed using the Penn Progressive Matrices (PMAT) test.
- Subjects were presented with a series of evolving patterns. They were tasked with selecting the correct next pattern from a list of options.
- The pattern completion task consisted of 24 items, arranged in order of increasing difficulty.

Methods

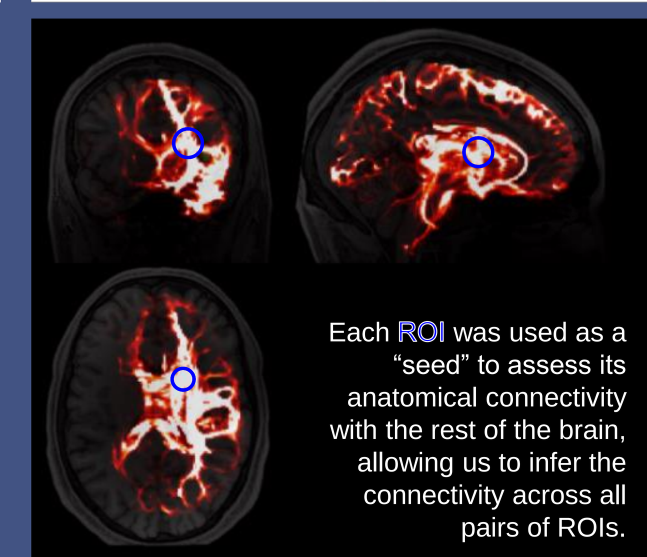
- We analyzed resting-state fMRI (rfMRI) and dMRI data from 127 HCP Subjects[10*].
- We used 264 unique regions-of-interest (parcellated into 14 cognitive networks) that were identified in a meta-study as belonging to 14 distinct cognitive regions[9].
  - The Cingulo-Opercular and Salience networks were merged into a single network (CON/SAL).



Yellow	Fronto Parietal
Red	Default Mode
Purple	Cingulo Opercular
Black	Salience
Gray	Memory Retrieval
Green	Dorsal Attention
Teal	Ventral Attention
Cyan	Sensory/Motor (Hand)
Orange	Sensory/Motor (Mouth)
Pink	Auditory
Blue	Visual
Pale Blue	Cerebellar
Brown	Subcortical
White	Uncertain



- rfMRI: We extracted the mean BOLD signal from voxels within each ROI at each time-point. We then correlated each ROI's mean time series to create a FC matrix for each subject.
- dMRI: We used a probabilistic tractography algorithm to assess the anatomical connectedness between any pair of ROIs to create a SC matrix for each subject.

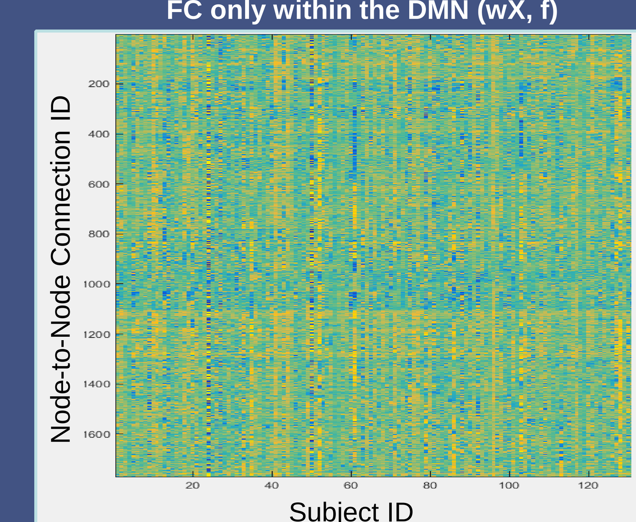


- We were able to index the FC and SC matrices as a function of network-membership to create "feature sets" that we used within a support vector regression leave-one-subject-out cross-validation framework. This allowed us to build a model on n-1 subjects' feature sets and predict the n[th] subject's Fluid Intelligence score.
- Our feature sets were indexed and manipulated as follows:

➢ Intra- vs. Inter-Network Connectivity
  - Within a single network (wX)
  - Bidirectionally across two networks (bXY)
  - Unidirectionally across two networks (uXY)

➢ SC vs. FC
  - Structural or Functional Only (s, f)
  - Masking the functional data to only include the values that showed either the highest or lowest structural connectivity (f_hs, f_ls)
  - Masking the structural data to only include the values that showed either the highest or lowest functional connectivity (s_hf, s_lf)
  - Multiplying the Structural and Functional (sxf)

Example Feature Set For N = 127 Subjects: FC only within the DMN (wX, f)



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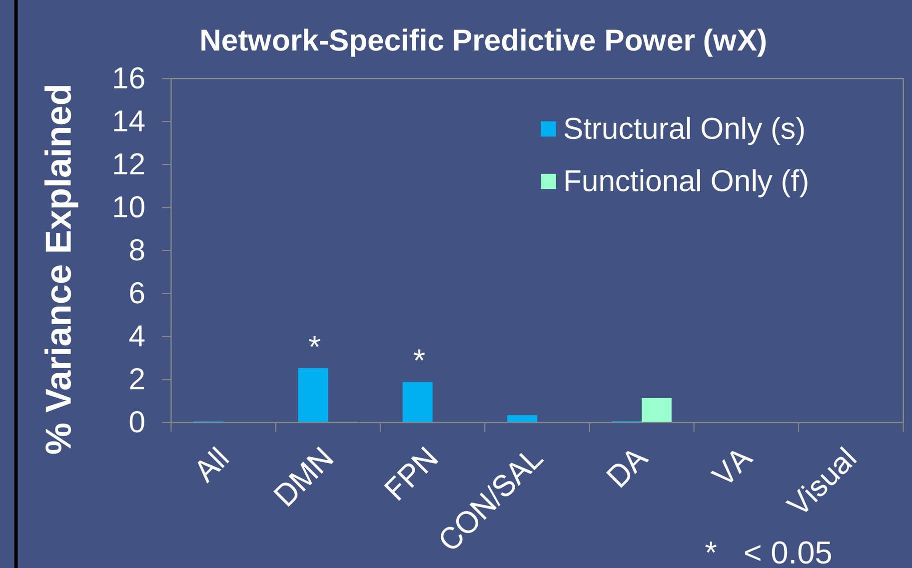
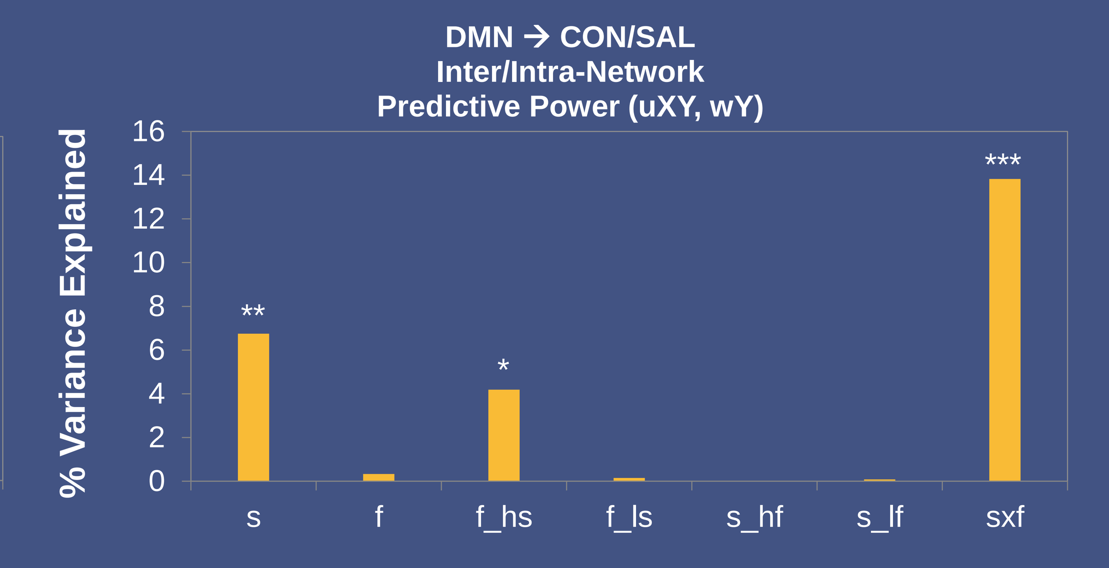
Results

- By correlating the array of predicted PMAT scores with the matched array of subjects' actual PMAT scores, we were able to obtain an R^2 value – the percent of the variance in Fluid Intelligence that our model was able to account for.
- When SC and FC were considered independently, only SC within the DMN and FPN was predictive of Fluid Intelligence.
- Given our hypotheses about the importance of across-network communication between DMN and CON/SAL, we examined whether including the connectivity between nodes of these networks would improve prediction of Fluid Intelligence. Interestingly, when FC data were limited to node pairs with high SC values, FC became predictive of Fluid Intelligence. Even more predictive was the interaction between SC and FC.





* < 0.05 ** < 0.005 *** < 0.00005

Conclusions

- These results demonstrate that individual differences in the connectivity within and between brain networks can explain variance in fluid intelligence abilities.
- When examining intra-network effects, we found that structural connectivity was a better predictor of fluid intelligence than functional connectivity, with reliable effects seen in the DMN and FPN.
- When examining inter-network effects, we found that structural connectivity between nodes of the DMN and CON/SAL networks was particularly informative. Functional connectivity was also informative, but only when constrained by high structural connectivity values.
- Most interestingly, the interaction feature set of both functional and structural values provided the highest predictive power for our model. Using both types of connectivity was notably more informative than just using either structural or functional connectivity alone.
- The CON/SAL has been shown to be a domain-general, task-control network,[6] while the DMN has been shown to be the opposite, whose decreased activity associates with task control.[3] Perhaps, what our model has extracted is the efficiency of the CON/SAL's ability to inhibit the DMN, so that a subject is not distracted by any internally generated narrative that could distract him/her from engaging in a complex cognitive task.

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