Goethe University Frankfurt am Main

Modular structure of intrinsic brain networks explains differences in human intelligence

Kirsten Hilger[1,2], Matthias Ekman[3], Christian J. Fiebach[1,2], Ulrike Basten[1]

[1]Department of Psychology, Goethe University, Frankfurt am Main, Germany; [2]IDeA Center for Individual Development and Adaptive Education, Frankfurt am Main, Germany; [3]Donders Institute for Brain, Cognition, and Behaviour, Radboud University Nijmegen, The Netherlands

1 Introduction

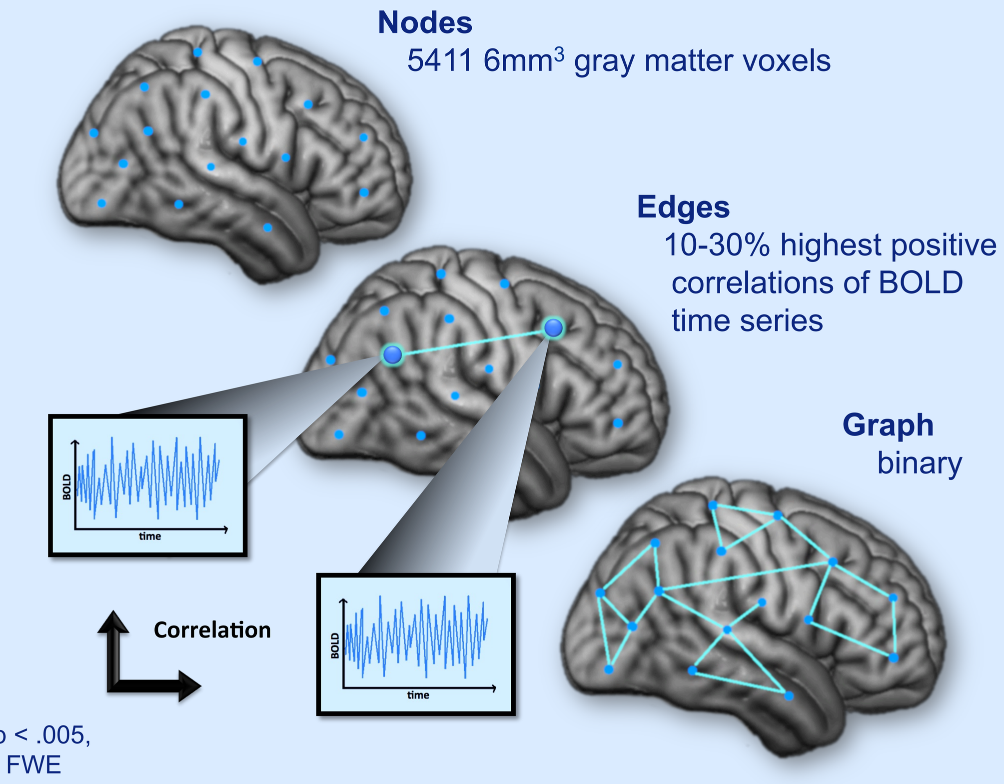
Intelligence and Network Modularity

- **Neural correlates of intelligence** were identified in the structure and function of **frontal and parietal cortex** (Jung & Haier, 2007; Basten et al., 2015)
- **Graph theory** provides a method for studying **functional brain networks** based on the coactivation of different brain regions
- Brain networks are characterized by a highly **modular organization** – consisting of subnetworks (i.e., modules) that are densely connected internally but only weakly coupled with the rest of the network (Sporns & Betzel, 2016)
- **It is an open question how individual differences in the modular organization of the brain may contribute to differences in general intelligence**
- The present study investigates this question, focusing on **whole-brain** and **node-specific** aspects of modular network organization

2 Methods I – Graph Theory

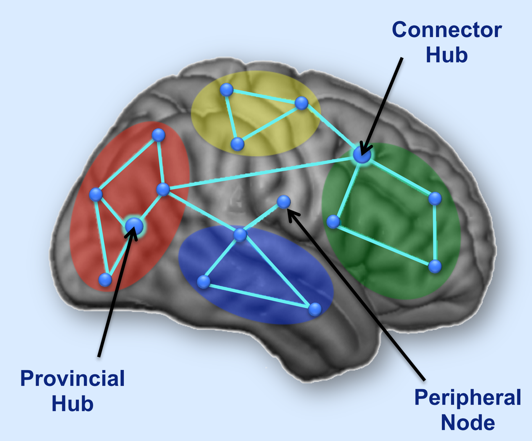
General Methods

- **Participants**: N = 309
  Age 18-60, *M* = 38.93, *SD* = 13.94
- **NKI Enhanced Rockland Sample**
  (Nooner et al., 2012)
- **Intelligence:** WASI FSIQ (Wechsler, 1999)
  FSIQ 67-135, *M* = 99.12, *SD* = 13.23
- **MRI-Acquisition:**
  → resting state functional scan
  5.05 min; 120 volumes; TR 2500 ms; TE 30 ms; FOV 216 x 216; voxel size 3x3x3 mm; flip angle 80°
- **Individual Level:**
  Graph construction and metrics
- **Group Level:**
  → Correlation Analyses (SPSS22, JASP)
  → General Linear Model (SPM8)
  Covariates of no interest: sex, age, handedness; Voxel-level p < .005, uncorrected + cluster-level *p* < .05; cluster size *k* > 26 voxels, FWE



Network Modularity

- **Optimization of Q:** See Methods II
  Louvain Algorithm (Blondel et al., 2008)



- **Modules:**
  Clusters of highly connected nodes

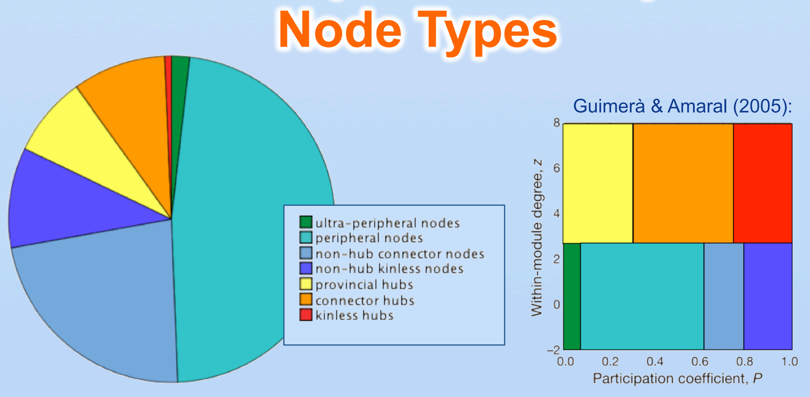
4 Results

No Association between Intelligence and Whole-Brain Modularity....

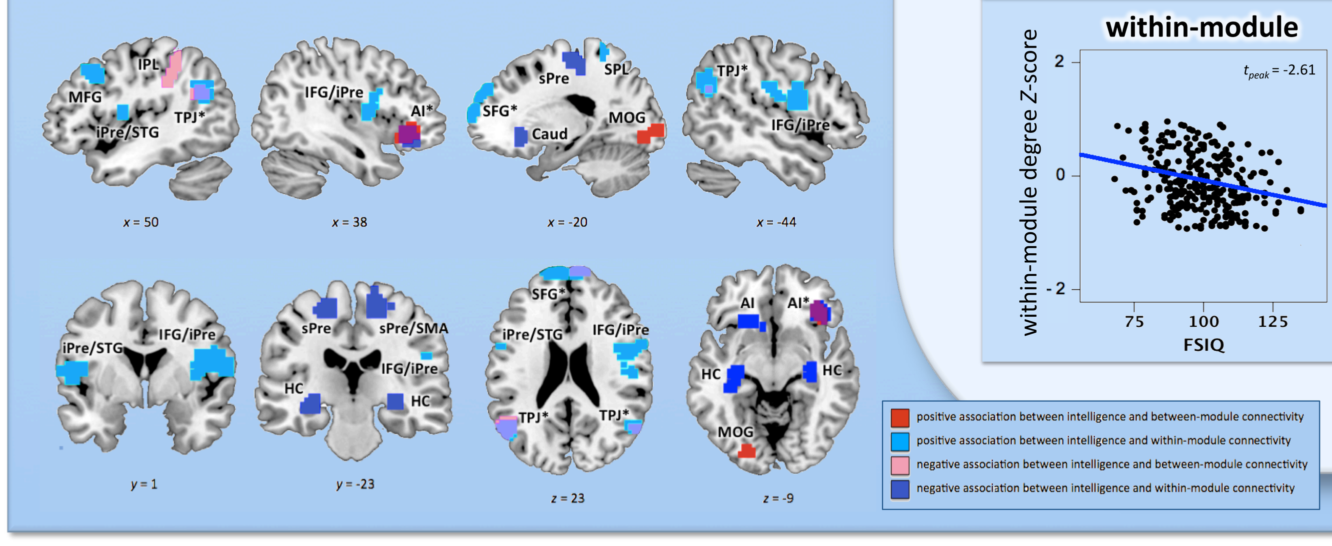
Whole-brain measure	*r*	*p*	BF_{01}
Modularity	.03	.569	3.16
Total number of modules	.04	.531	3.07
Average size of modules	-.04	.466	2.86
Variability in average size of modules	.05	.355	2.50

Note: BF_{01}, Bayes Factor for Bayes linear regression models predicting FSIQ from whole-brain measure by controlling for age, sex, handedness

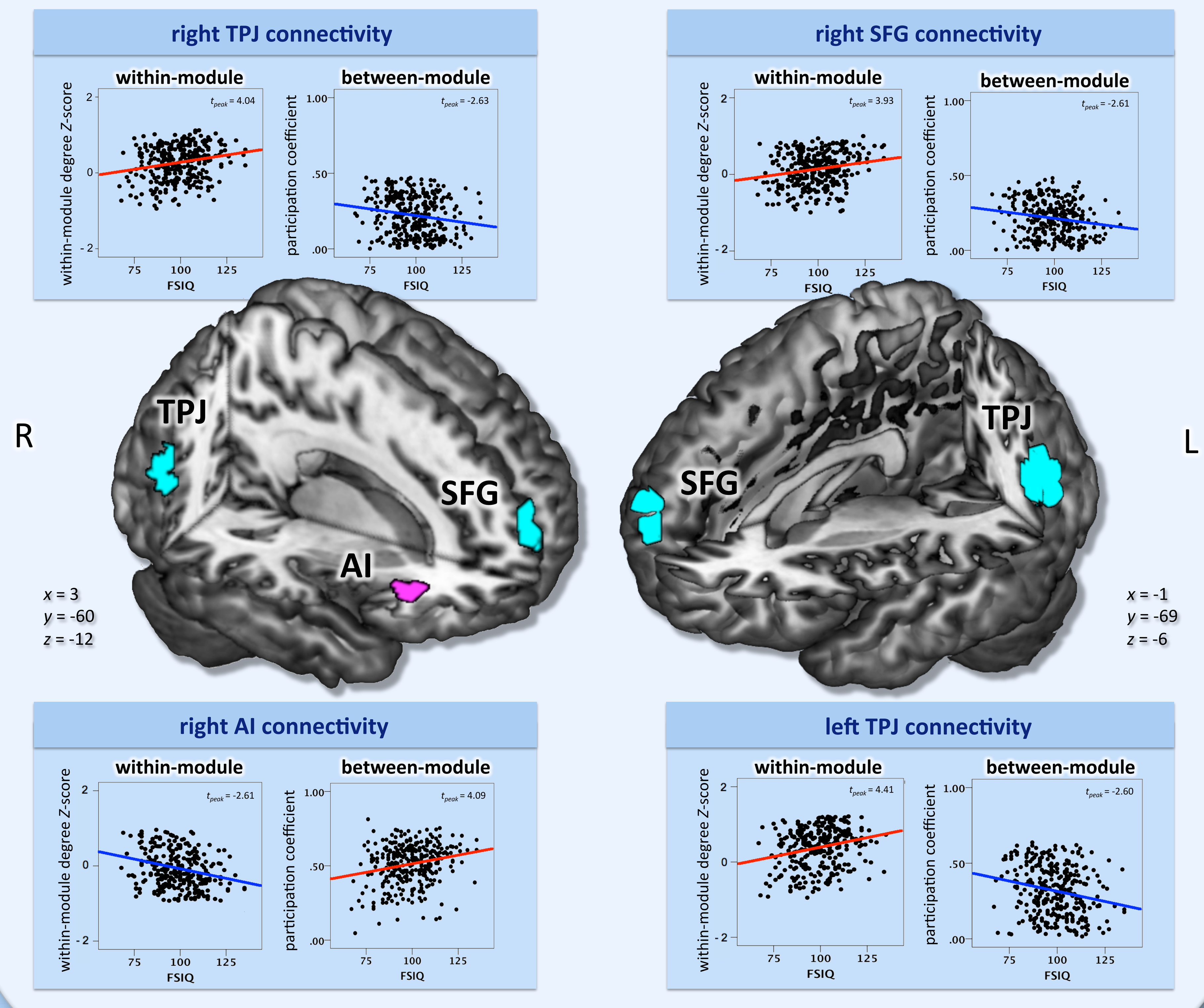
....or the Proportions of Specific Node Types



Associations between Intelligence and Profiles of Between-Module OR Within-Module Connectivity

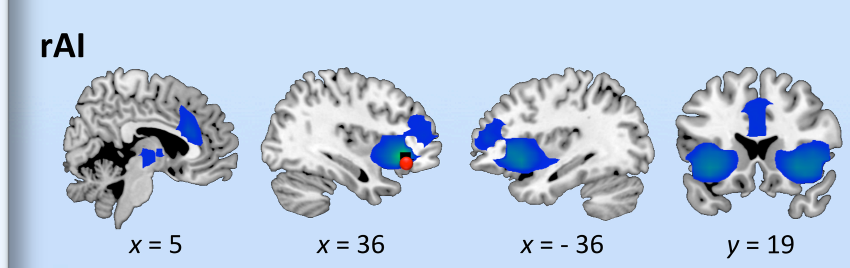


Associations between Intelligence and Profiles of Between-Module AND Within-Module Connectivity

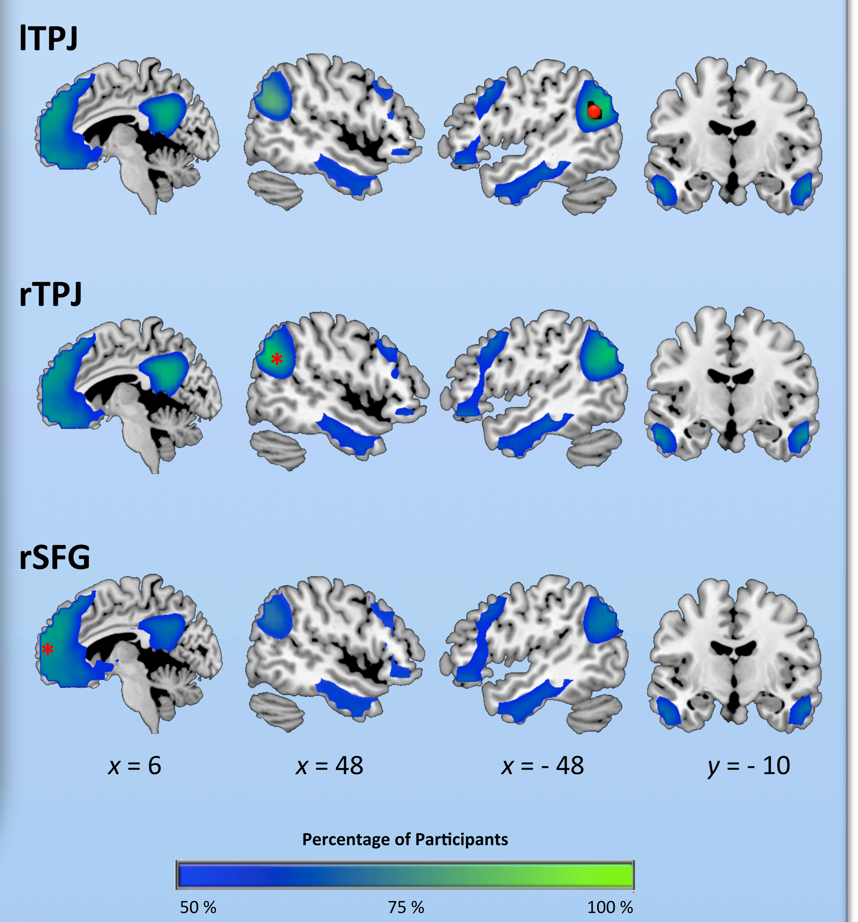


Module Membership Analysis* for Intelligence-Related Regions

Module of the AI effect resembles the Salience Network



Module of the TPJ & SFG effects resembles the Default Mode Network



* = Figures illustrate nodes that were assigned to the same module as peak node (● / * = approximate location) of intelligence-related region in > 50% of participants.

3 Methods II – Modularity Analysis

Whole-Brain Aspects of Modular Organization

- Modularity (*Q*)
  (Newman & Girvan, 2004)

$$Q = \frac{1}{2m}\sum_{ij}^{n}[a_{ij} - p_{ij}]\,\delta(\sigma_i, \sigma_j)$$

Node-Specific Aspects of Modular Organization

- Participation Coefficient (*P*):
  → *between-module connectivity*

$$p_i = 1 - \sum_{m \in M}\left(\frac{k_i(m)}{k_i}\right)^2$$

- Within-Module Degree Centrality Z-Score (Z):
  → *within-module connectivity*

$$z_i = \frac{k_i(m_i) - \bar{k}(m_i)}{\sigma^{k(m_i)}}$$

Functional Cartography

- Classification of nodes regarding their profile of between-module connectivity (*P*) and within-module connectivity (*Z*)
  (Guimerà & Amaral, 2005)

5 Summary & Conclusions

- While we observed no intelligence-related differences in modularity at a whole-brain level, our study demonstrates **intelligence-related differences in region-specific aspects of modular brain network organization**
  - **In more intelligent people ...**
    - ... a distinct set of **frontal and parietal** brain regions exhibited different profiles of within-module **and/or** between-module connectivity
    - ... right **AI**, bilateral **TPJ**, and right **SFG** were associated with both aspects, i.e., between-module **and** within-module connectivity, in opposite direction
- These results corroborate the critical **relevance of frontal and parietal brain regions** for human intelligence (e.g., Jung & Haier, 2007)
- As AI has been associated with the **detection of salient and relevant information** (Corbetta et al., 2008), and TPJ with the **shielding of cognitive processing against interference** (Anticevic et al., 2010), we conclude that superior cognitive performance may result from **optimizing of both processes simultaneously**

6 References

Anticevic et al. (2010). When less is more: TPJ and default network deactivation during encoding predicts working memory performance. *NeuroImage, 49*(3), 2638–2648.

Basten et al. (2013). Intelligence is differentially related to neural effort in the task-positive and the task-negative network. *Intelligence*, 41, 517.

Blondel et al. (2008). Fast unfolding of communities in large networks. *Journal of Statistical Mechanics: Theory and Experiment*, 10008, 6.

Corbetta et al. (2008). The Reorienting System of the Human Brain: From Environment to Theory of Mind. *Neuron, 58*, 306–324.

Guimerà & Ameral (2005). Functional cartography of complex metabolic networks, *Nature*, 433(February), 895–900.

Jung & Haier (2007). The Parieto-Frontal Integration Theory (P-FIT) of intelligence: converging neuroimaging evidence. *The Behavioral and Brain Sciences,* 30, 135.

Newman & Girvan (2004). Finding and evaluating community structure in networks. *Phys. Rev*. E 69(2):026113

Nooner et al. (2012). The NKI-Rockland Sample: A Model for Accelerating the Pace of Discovery Science in Psychiatry. *Frontiers in Neuroscience*, 6(October), 152.

Sporns & Betzel (2016). Modular Brain Networks. *Annual Review of Psychology*, 67(September 2015), null. **Wechsler, D. (1999).** *Wechsler Abbreviated Scale of Intelligence*. The Psychological Corporation: Harcourt Brace & Company. New York, NY.

Acknowledgement

Supported by the German Ministry of Education and Research (Bernstein Center, BMBF; 01GQ1003A), the LOEWE initiative of the State of Hessen, and a VIDI grant from the Netherlands Organization for Scientific Research (Grant 45209006 to CJF). CJF is furthermore supported by ERC Consolidator Grant #617891.

The data used for the present study was acquired by the Nathan S. Kline Institute for Psychiatric Research (NKI), founded and operated by the New York State Office of Mental Health and Research Foundation for Mental Hygiene. Additional project support provided by the NKI Center for Advanced Brain Imaging (CABI), the Brain Research Foundation (Chicago, IL), the Stavros Niarchos Foundation, and NIH grant P50 MH086385–S1. The NKI takes part in the 1000 functional connectomes project, which is an international neuroimaging data sharing initiative (INDI, www.fcon_1000.projects.nitrc.org/indi/pro/nki.html).

Email: hilger@psych.uni-frankfurt.de