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General, crystallized and fluid intelligence are not associated with functional global network efficiency: A replication study with the human connectome project 1200 data set

J.D. Kruschwitz [a,b,*,1], L. Waller [a,1], L.S. Daedelow [a], H. Walter [a,2], I.M. Veer [a,2]

[a] Charité - Universitätsmedizin Berlin, Corporate Member of Freie Universität Berlin, Humboldt-Universität zu Berlin, and Berlin Institute of Health, Department of Psychiatry and Psychotherapy CCM, Berlin, Germany

[b] Collaborative Research Centre (SFB 940) "Volition and Cognitive Control", Technische Universität, Dresden, Germany

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ABSTRACT

One hallmark example of a link between global topological network properties of complex functional brain connectivity and cognitive performance is the finding that general intelligence may depend on the efficiency of the brain's intrinsic functional network architecture. However, although this association has been featured prominently over the course of the last decade, the empirical basis for this broad association of general intelligence and global functional network efficiency is quite limited. In the current study, we set out to replicate the previously reported association between general intelligence and global functional network efficiency using the large sample size and high quality data of the Human Connectome Project, and extended the original study by testing for separate association of crystallized and fluid intelligence with global efficiency, characteristic path length, and global clustering coefficient. We were unable to provide evidence for the proposed association between general intelligence and functional brain network efficiency, as was demonstrated by van den Heuvel et al. (2009), or for any other association with the global network measures employed. More specifically, across multiple network definition schemes, ranging from voxel-level networks to networks of only 100 nodes, no robust associations and only very weak non-significant effects with a maximal R^2 of 0.01 could be observed. Notably, the strongest (non-significant) effects were observed in voxel-level networks. We discuss the possibility that the low power of previous studies and publication bias may have led to false positive results fostering the widely accepted notion of general intelligence being associated to functional global network efficiency.

Introduction

Resting-state functional connectivity is hypothesized to reflect the brain's intrinsic functional architecture, providing the foundation for task-related activity and behavior. One hallmark example of a link between global topological network properties of complex functional brain connectivity and cognitive performance is the finding that general intelligence may depend on the efficiency of the brain's intrinsic functional network architecture, i.e., the ease with which brain regions communicate. Specifically, lower characteristic path length (an inverse of global efficiency calculated as the average of direct and indirect connection strengths between all brain regions) was associated with higher scores of general intelligence (van den Heuvel et al., 2009).

As the operationalization of the 'efficient brain' conveniently allows the scientist to conceptualize the biology of intelligence like one would characterize a machine or a computer, neuroscientists started to investigate the association of optimal brain functioning and intelligence in large-scale brain networks with graph theoretical methods. Following the initial observation of lower characteristic path length corresponding to higher scores of general intelligence (van den Heuvel et al., 2009), increasing evidence from fMRI (Pamplona et al., 2015), high-resolution resting-state EEG (Langer et al., 2012), and diffusion weighted imaging (DTI) studies (Li et al., 2009; Zalesky et al., 2011; Yeo et al., 2016) has also contributed to the notion that the brain's global network efficiency is

* Corresponding author. Charité - Universitätsmedizin Berlin, Corporate Member of Freie Universität Berlin, Humboldt-Universität zu Berlin, and Berlin Institute of Health, Department of Psychiatry and Psychotherapy CCM, Berlin, Germany.

E-mail address: johann.kruschwitz@charite.de (J.D. Kruschwitz).

[1] Shared first author.

[2] Shared senior author.

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Table 1
Demographic characterization of the sample: 1096 participants from the Human Connectome Project 1200 subjects release.

Variable	Data
Gender (male/female)	500/596
Age	28.8 ± 3.7 years
Handedness	66.0 ± 44.0
Mean framewise displacement (FD)	0.09 ± 0.03 mm
Penn Progressive Matrices	16.9 ± 4.8
Dimensional Change Card Sort	102.3 ± 9.9
Flanker	101.7 ± 10.1
Oral Reading Recognition	106.9 ± 14.8
Picture Vocabulary	109.2 ± 15.4
Picture Sequence Memory	105.0 ± 16.6
Pattern Comparison Processing Speed	103.7 ± 20.0
List Sorting Working Memory	103.3 ± 13.2
Crystallized Cognition Composite Score	108.1 ± 13.8
Fluid Cognition Composite Score	103.2 ± 9.0
Total Cognition Composite Score	104.6 ± 8.6

*Age, handedness, FD, and scores are depicted as mean ± standard deviation.

associated with higher intelligence.

However, although this association has been featured prominently over the course of the last decade, the empirical basis for this broad association of general intelligence and global functional network efficiency is actually quite limited. First, conceptualizations of intelligence varied considerably between previous studies, which makes it difficult to draw conclusions about 'general intelligence' and potential associations to network efficiency. Second, only two other studies investigating functional brain networks could partially replicate the association between intelligence and a more effective functional brain network organization, reporting medium effect sizes (Langer et al., 2012; Pamplona et al., 2015). Specifically, by using high-density resting-state EEG, Langer et al. (2012) demonstrated an association between characteristic path length and a test measuring non-verbal abstract reasoning with Raven's Progressive Matrices (as a type of fluid intelligence; $r = 0.3$), while Pamplona et al. (2015), using resting-state fMRI, only observed an association between global efficiency and verbal comprehension (as a type of crystallized intelligence; $r = 0.4$). Importantly, Pamplona et al. (2015) did not observe a significant effect for general intelligence as measured by the sum score of the Wechsler Adult Intelligence Scale (WAIS). A third study (Hilger et al., 2017), which can be considered the most direct replication attempt of the original study (computation of global network efficiency from voxel-wise networks in 54 subjects), did not observe any association of global network efficiency derived from resting-state fMRI data to general intelligence as measured with the Wechsler Abbreviate Scale of Intelligence (WASI).

In the current study, we set out to replicate the previously reported association between general intelligence and global functional network efficiency (van den Heuvel et al., 2009), using the large sample size and high quality data of the Human Connectome Project (HCP). More specifically, we examined the association of global network efficiency derived from whole-brain voxel-level networks (as the original study of van den Heuvel et al., 2009) and general intelligence (conceptualized as the weighted sum of crystallized and fluid intelligence; Gf-Gc Theory; e.g., Cattell, 1971) and extend the original study by testing for separate associations of crystallized and fluid intelligence (as well as their sub-scores) with global network efficiency, characteristic path length, and global clustering across multiple methods to derive functional connectivity in 8 network schemes: voxel-wise data at 4 mm isotropic resolution with all voxels (21637 voxels), voxel-wise data at 4 mm isotropic resolution with only grey matter voxels (16 071 voxels), automated anatomical labeling (116 regions; Klein and Tourville, 2012), the atlas by Power et al., (2011) (264 regions), the atlas by Craddock et al., (2012) (840 regions), and 100, 200, and 300-component group-ICA solutions as provided by the Human Connectome Project (HCP; Smith et al., 2015), thus offering a comprehensive replication of results previously reported in literature.

Methods

Subjects

All 1096 participants with resting-state functional magnetic resonance imaging from the human connectome project (HCP) 1200 subjects release (Glasser et al., 2016) were entered into the analysis. Between 7 and 97 subjects were excluded due to missing values in the intelligence measures or missing neuroimaging data, depending on the specific measure and preprocessing scheme. For example, group-ICA data are only provided by the HCP for 1003 subjects. As a result, sample size varied between 999 and 1096. A demographic characterization of the sample is depicted in Table 1.

Behavioral data

To replicate the previously reported associations of higher general intelligence and elevated functional global network efficiency, we adopted the intelligence concept incorporated in the Wechsler intelligence scales. Specifically, to conceptualize general intelligence as the weighted sum of crystallized and fluid intelligence (Gf-Gc Theory; e.g., Cattell, 1971), we included the following NIH Toolbox Cognition (NIHTB-CB) composite scores (Heaton et al., 2014) in the current study: *Crystallized cognition* (calculated as the sum score of the scales: Picture vocabulary and Oral reading) and *Fluid cognition* (sum score of the scales: Dimensional card sort, Flanker, Picture sequence memory, List sorting, Processing speed). To obtain a global measure of intelligence the two composite scores were aggregated according to Heaton et al. (2014) to a *Total Cognition* Score that obtains convergent validity of $r = 0.89$ to general intelligence, as measured with WAIS-IV (Heaton et al., 2014). For comprehensiveness, we included an additional measure of fluid intelligence (the Raven's Progressive Matrices test; Bilker et al., 2012), as provided in the human connectome project 1200 subjects release. This

Table 2a
Covariance between the employed intelligence measures as determined by correlational analyses.

	CS	FL	OR	PV	SM	PS	LS	RM	GC	GF
FL	0.52									
OR	0.25	0.18								
PV	0.19	0.20	0.70							
SM	0.21	0.15	0.21	0.20						
PS	0.42	0.39	0.16	0.16	0.20					
LS	0.21	0.14	0.36	0.34	0.34	0.18				
RM	0.22	0.13	0.48	0.50	0.30	0.15	0.36			
GC	0.24	0.21	0.92	0.92	0.22	0.18	0.38	0.53		
GF	0.66	0.60	0.35	0.33	0.64	0.74	0.57	0.35	0.37	
G	0.59	0.54	0.68	0.67	0.57	0.63	0.60	0.50	0.73	0.90

CS - Dimensional Change Card Sort, FL - Flanker, OR - Oral Reading Recognition, PV - Picture Vocabulary, SM - Picture Sequence Memory, PS - Pattern Comparison Processing Speed, LS - List Sorting Working Memory, RM - Raven's progressive matrices, GC - Crystallized Cognition Composite Score, GF - Fluid Cognition Composite Score, G - Total Cognition Composite Score. All $p < .05$, bonferroni corrected.